

Dr. Claude Bernard 8
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OF THE
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NEW YORK, 1873.

THE EFFECTS
OF
HIGH ATMOSPHERIC PRESSURE,
INCLUDING THE
CAISSON DISEASE.

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REPORT
ON
THE EFFECTS OF HIGH ATMOSPHERIC PRESSURE,
INCLUDING THE
CAISSON DISEASE.

BY ANDREW H SMITH, M. D.,

SURGEON TO THE COMPANY.

To the Board of Directors of the New York Bridge Company:

GENTLEMEN:—

This Report was originally intended simply to present my own experience as Surgeon to the New York Bridge Company during the sinking of the second caisson. But in endeavoring to compare this experience with that of others who had had opportunities of observing the effects of high atmospheric pressure, I found that the literature of the subject consisted only of isolated reports by different individuals, in different languages, and having little or no reference one to another, so that a great deal of research was required to obtain a connected view of the subject. It seemed to me, therefore, desirable not to add another to the list of disjointed fragments, but rather to incorporate my own observations with the existing material, and thus present in one view a *résumé* of our actual knowledge upon the subject. This I have endeavored to do briefly in the following pages. For whatever is purely theoretical, however, and especially as regards the pathology of the Caisson Disease, I must accept the entire responsibility, unless reference is made to other authority.

CHAPTER FIRST.

HISTORY.

The discoveries of Torricelli, in 1643, which led to his invention of the barometer, and the further elucidation by Pascal of the principles of atmospheric pressure, five years later, were followed by confused and contradictory speculations on every hand as to what would be the effect upon animal life if the barometric changes so eagerly observed assumed a wider range.

Dr. Henshaw, an English physician, published an essay in 1664, in which he proposed to treat diseases by varying the pressure of the atmosphere by which the patient was surrounded. His idea was to have a room (*domicilium*) constructed of masonry, and made air-

tight, in which the sick person could remain in an atmosphere which was to be either rarefied or condensed by the action of an organ bellows.

He fancied that acute diseases would be benefited by an increased pressure, while chronic diseases on the other hand demanded a rarefied atmosphere. His views seem, however, to have been purely theoretical, as there is no record of any serious attempt to reduce them to practice.

More than a century elapsed before the subject again awakened the attention of scientific men. In the year 1783 the Academy of Sciences of Haarlem offered a prize for a description of the best apparatus for experimenting upon the effects of compressed air, with a record of experiments made by means of it on animal life, the growth of plants, and the inflammability of the different gases. This prize, however, was not contended for until more than half a century later.

Diving-bells were brought into use as early as the beginning of the sixteenth century, but the condensation of the air within them does not seem to have attracted attention, at least as affecting the occupant. Indeed, whatever influence the increased pressure may have exerted was masked by the impurity of the air, which, in the machines first employed, was not renewed. It was found that the strongest man could not remain under water longer than an hour; but the ill effects experienced were attributed to the heat which accumulated in the bell, and which was supposed to affect respiration. Subsequently, when an apparatus was added for supplying fresh air, it was remarked that the workmen felt no inconvenience whatever.

The first observations of real value upon the effects of high atmospheric pressure were made at Howth, near Dublin, in the year 1820, by a distinguished Russian physician named Hamel. In the course of some engineering work in which diving-bells were employed, Dr. Hamel had the opportunity of studying the effects of compressed air, not only upon the workmen, but also upon himself. In describing his own experience, he states that at the depth of five or six feet severe pain was felt in the ears, which was relieved in a measure by swallowing. At fifteen or sixteen feet, there was a noise in the ears like an explosion, followed by entire relief from the pain. His respiration was perfectly easy.

The ascent was accomplished with much less inconvenience than the descent.

Hamel states that one of the workmen became so accustomed to the air of the bell as to be uncomfortable under the usual atmospheric pressure.*

In 1826, Dr. Colladon published observations made at the same time and place as the above. In winter the hours of work in the bells were five daily; in summer, five and ten alternately. Toward the close of the work, each day the men became very much exhausted, and were given a little brandy and a bit of bread. Those newly employed suffered with pain in the head and ears, and were often affected with colic and diarrhea, which last were attributed to cold and wet. Increase of appetite and augmentation of the urine were observed. In some cases, deafness was relieved, and one case of asthma was entirely cured.

In 1835, Junod published the results of extensive experiments upon compressed air as a remedial agent.* This was the beginning of a series of memoirs upon this subject appearing in rapid succession in France and Germany. Institutions sprang up in various parts of the Continent designed to afford the most approved facilities for this mode of treatment, and the results obtained were, and continue to be, highly satisfactory. The "compressed air-baths" are especially useful in the treatment of pulmonary diseases and of dyspepsia.

But as the pressure employed in these baths is comparatively slight, usually not more than eight or ten pounds to the square inch, the effects observed differ widely from those produced by the high pressure employed for engineering purposes. This difference is not only in degree, but also in kind, and therefore the literature relating to compressed air as a remedy,† although rich, and in itself very interesting, throws but little light upon the subject of this discussion. It is probable, however, that the investigations in this direction of Junot, Tabarie, and Pravaz first suggested the employment of compressed air as a substitute for pumps in mining operations.

To M. Triger, a French engineer, belongs the credit of first conceiving and carrying out a plan by which atmospheric pressure was made to keep back the water flowing into a mining shaft. It had long been known that the valley of the Loire was underlaid by an extensive bed of coal, but, inasmuch as in order to reach the coal it was necessary to pass through twenty metres of quicksand in communication with the water of the river, the engineering difficulties had been considered, until the advent of Triger, as insurmountable. To keep a shaft dry by pumping was equivalent to pumping out the Loire. To meet this difficulty, Triger conceived the idea of sinking an iron tube through the quicksand, the interior of the tube being kept free from water during the excavation by condensing the air in

* Archives Generales de Medicine.

† Those interested in this subject will find it exhaustively treated in an admirable work by Dr. Rudolf v. Vivenot: "Zur Erkenntniss der Physiologischen Wirkung und der Therapeutischen Anwendung der Verdichteten Luft." Erlangen, May, 1872.

the tube to the point of counterbalancing the pressure of the water. After some preliminary experiments made by the aid of Tabarie's remedial bath, the work was begun in 1839, near Chalonnes. A tube of iron, seventy feet long by three and one-half feet in diameter, was provided, with a box or chamber at the top, such as we now call an air lock, having a valve above opening inward, and another below opening downward into the tube. These valves were of such a size as to permit the passage of the workmen, and the removal of the excavated material. The workmen having passed into the lock, the upper valve was closed, and a cock opened communicating with the main tube, where the air was compressed sufficiently to keep back the water, the compression being effected by means of condensers worked by steam. The pressure in the lock having become equal to that in the main tube, the lower valve was opened and the workmen descended into the tube. In going out, or in sending out material, the process was reversed. The tube was forced down into the earth in proportion as the workmen excavated at the bottom.

It will thus be seen that the first attempt at this mode of working embraced all the essential features of the method as now employed.

In his undertaking, Triger was completely successful. The quicksand was passed and the coal reached, and at the same time there was given to the world a new engineering resource of exceeding value.

It is much to be regretted that these operations were not carried on under the eye of a competent medical observer. The only report we have of them is by M. Triger himself,* and it is natural that the engineering rather than the medical aspect of the question should principally engage his attention. His notice of the effects of the compressed air upon the workmen is extremely meagre, and is summed up in the following points :

" 1. At the pressure of three atmospheres it is impossible to whistle, while a lower pressure does not produce this effect.

" 2. In the compressed air, every one speaks through the nose, and this is the more noticeable the higher the pressure.

" 3. All the laborers remarked that in ascending the ladders they were much less out of breath (*moins essoufflés*) than when mounting to a similar height in the open air.

" 4. A laborer who had been deaf since the seige of Antwerp, (1832,) always heard more distinctly in the compressed air than any of his comrades.

" No illness was occasioned among the laborers except that two of them, after seven hours of labor in the tube, experienced severe pains

* Comptes Rendus. T. XIII. 1841. "Memoire sur un appareil à air comprimé pour le percement des puits, etc. Par M. Triger."

in the arms and knees, coming on about half an hour after ascending into the open air." These are the first recorded cases of what I have named the *Caisson Disease*.

About the year 1850 compressed air was first employed in the sinking of piers. A railway bridge was constructed over the Medway, between Rochester and Chatham, the piers of which rested on a basis composed of hollow iron piles, forty-two inches in diameter, each of which was sunk in precisely the same manner as the tube of Triger. I have not been able to find any record of the effects of the compressed air upon the men employed, though some accidents due to this cause are stated to have occurred.

The results obtained by Triger led, in 1845, to the application of the same principle to the working of the mine at Douchy, Department du Nord. The laborers in this case were under the supervision of MM. B. Pol and T. J. J. Watelle, who published an extremely interesting memoir upon the subject.*

The entire *personnel* comprised sixty-four men, who were employed at two different epochs, under different pressures. They were divided into gangs of six or seven each, laboring alternately four hours twice a day. At first, the time allowed for locking out was one-fourth of an hour, but as the pressure increased it was extended to half an hour. The maximum pressure was three and one-half atmospheres.

After each shift the men bathed and put on dry clothes, when a cup of bouillon and a glass of Bordeaux were served to each man.

As the number of cases of illness increased, a sort of *ambulance*, or temporary hospital, was established at the spot.

At a pressure of two and three-quarter atmospheres, Pol experienced in his own person the pain in the ears while locking in, and the ease with which a ladder is ascended in the compressed air, confirming in this latter particular the observation of Triger. The soot from the candles with which the air of the shaft was loaded, produced a troublesome cough, attended with black expectoration. The mucous membrane of the nose and throat became stained with it, and even the faeces were blackened.

While locking out there was experienced by all the men a feeling of suffocation. Pol was the first to perceive that the real danger was in passing from the condensed into the normal atmosphere, instead of in passing in the reverse direction. On emerging into the open air, he found that his pulse, which had fallen while in the caisson from seventy, its normal standard, to fifty-five, rose suddenly to eighty-five. When the pressure had increased to three and one-half at-

* Memoire sur les Effets de la Compression de l'air, etc. Annales d' Hygiene Publique et de Med. Legale, 1854.

mospheres, he again entered the caisson. The unpleasant sensations already referred to were found to be intensified. In blowing his nose he accidentally discovered that this operation gave much more perfect relief to the ears than the act of swallowing. In speaking he found that the tongue moved stiffly and with difficulty. Sounds were not heard with their usual intensity. The secretion of urine was decidedly increased. After reaching home he was seized with severe pain in one arm and shoulder, and in the walls of the chest. Afterward, there were chills, followed by vomiting. Rest in the horizontal position, and the use of sudorifics, restored him to his usual health by the following day.

Of the sixty-four men employed, thirty-nine continued until the work was completed, and twenty-five were compelled to give up their places, not being able to support the effects of the compressed air.

The most usual affection was muscular pains, occurring either alone or ushering in other symptoms. Pulmonary congestion occurred in several cases, but it may well be questioned whether the excessive impurity of the air, as evinced by the amount of soot it contained, may not have had much to do with the production of this otherwise unusual result. Other symptoms which he describes, such as great hebitude, incoherence of speech, tottering gait, etc., indicate the effects of carbonic acid, and as no mention is made of any provision for removing the products of combustion and respiration, this gas must have been present in considerable quantity.

The conclusions arrived at by Pol are as follows :

1. A pressure of four and one-quarter atmospheres is not in itself dangerous, but the return into the open air may cause serious accidents, and even sudden death. The danger is in proportion to the previous pressure.
2. The pathological changes consist in visceral congestions, among which congestion of the lungs and brain take the foremost rank.
3. The tendency to these congestions increases with the age, at least between eighteen and fifty-five.
4. Not the period of greatest strength, which is between thirty and forty, but that between eighteen and twenty-six is that which is exposed to the least danger.
5. Experience teaches that the ill effects are in proportion to the rapidity with which the transition is made from the compressed air to the normal atmosphere.
6. Unimportant troubles, such as cough, gastric symptoms, etc., may be due to the smoke from the lamps.
7. The treatment is not different from that which is usual when like symptoms arise from other causes. The first indication is to

bring about a reaction, which is in turn to be combatted when it exceeds physiological limits.

8. One case seems to indicate that the quickest and safest means of restoration is an immediate return into the compressed air.

9. Cold to the surface is the best means for restoring the function of the skin.

About the year 1856 this method of excavation was employed in the coal mines at Eischweiler, near Aix-le-Chapelle. No phenomena were observed differing from those already described, except that bleeding from the nose occurred in several cases on emerging into the open air.*

About 1858-9 excavation by the aid of compressed air was extensively employed in laying the foundations of piers for bridges. Among the first of these were the Quarantine Bridge at Lyons, the bridge at Macon, and the chain bridge over the Thiess. A report upon the latter is contained in the "Annales des Ponts et des Chaussees," for 1859. Ringing and pain in the ears were complained of by the laborers, as also pain in the teeth, and in the muscles generally. The sound of the voice was observed to be changed, and the breathing to be quickened. The return to the open air was often followed by bleeding at the nose. Men of several different nationalities were employed, and it was observed that the Hungarians and the French suffered least, while the Italians, Germans, and Sclavonians were most affected.

In 1859, the mines at Eischweiler were re-opened, compressed air being again employed. The pressure did not exceed two and one-half atmospheres. The duration of the shifts was six hours. Excessive sweating was observed, followed by thirst after leaving the mine. There was generally impairment of appetite.†

At the same time work was being carried on by similar means in the coal mines at Lüttich. According to the statement of the superintendent, the men became so emaciated that after a few months they could no longer be prevailed upon to continue the work, notwithstanding large wages were offered and the most nourishing food provided.

Perhaps the most extensive work undertaken in Europe by the aid of compressed air was the bridge over the Rhine, at Strasburg. An account of this is given by Dr. François, who had medical charge of the workmen.‡

* Vivenot. *Wirkung der Verdichteten Luft.*

† Ibid.

‡ "Des effets sur les ouvriers travaillant dans les caissons servant de base aux piles du Pont du Grand Rhin." *Annales d' Hygiene Publique et de Med. Legale.* T. XIV. 1860.

The caissons were fourteen in number, each seven metres long by five and eight-tenths wide and three and five-tenths high. The locks were two metres in diameter and four metres in height.

François refers to the progressive impairment of hearing as the pressure increased in the lock; to the increase of temperature from the compression of the air; and to the accumulation of soot in the air-passages, which had been before observed by other writers. On going out of the caissons, intense pain in the ears sometimes occurred, together with muscular and arthritic pains. A very annoying itching of the skin was sometimes felt. Cerebral congestions, haemoptysis, and bleeding at the nose, were also not uncommon. Sometimes these various affections occurred immediately upon leaving the caisson, while in other cases they were deferred for several hours. In two or three instances the men were able to walk home, and afterward fell "as if struck by lightning." The attacks usually passed off quickly. Only one death occurred, and that resulted from breaking the rule as to the length of time to be occupied in locking out.

The rule established was to allow from four to five minutes in locking out when the pressure was one-quarter to one-half an atmosphere; six to seven minutes for one atmosphere; ten for one and one-half atmospheres; twelve for two atmospheres. A woolen vest was provided for each man to be put on when leaving the caisson, in order to guard against the effect of the sudden reduction of temperature which resulted from the expansion of the air in the lock. It was observed that the foremen suffered much less than the laborers, since their superior intelligence enabled them to realize the necessity of observing the rules.

Some other points observed by this writer will be referred to hereafter in their proper connection.

In the year 1863, Dr. Antoine Ed. Foley published a monograph comprising his observations upon the effects of condensed air as demonstrated during the sinking of the piers for a bridge at Argenteuil.* The original work not being accessible, I avail myself of the *résumé* contained in the treatise of Vivenot, of which I give a somewhat condensed translation from the German.

Foley observes that during the time that the pressure was increasing, the organs of hearing were always, without exception, affected. Occasionally neuralgic pains were felt darting through the forehead, the nasal cavities, and the jaws; the voice acquired a metallic sound; whistling became impossible; in a few cases stammering was induced. Taste, smell, and the sense of touch lost their acuteness. There was experienced a sense of warmth in the skin, as if one were

* "Du travail dans s'air comprimé, étude médicale, hygiénique et biologique faite au pont d'Argenteuil." Paris, 1863.

in a drying-room. The pulse became small and thready, sometimes imperceptible to the touch. The venous blood had a bright red hue.

The lungs seemed to increase in development, while the motion of the ribs was less. Shortness of breath was not often observed. Increase of appetite was soon experienced, but never thirst.

While the pressure remained stationary, all subjective phenomena disappeared, to return again during the locking out. Ringing of the ears and bulging of the ear drums were observed; taste and smell returned: a prickling sense of warmth was felt in the nostrils, which was sometimes followed by bleeding at the nose. At the same time the rapid decline of the temperature from the expansion of the air caused extreme chilliness.

At first the laborers remained in the compressed air four hours at a time, twice a day, with an interval of rest. But as the pressure increased it was found necessary to diminish the hours of labor.

The ill effects upon the workmen were almost entirely confined to a distressing itching of the skin and painful congestive swelling of the muscles. They observed that the appetite was increased while thirst was diminished. The flow of urine was also greater than usual.

A remarkable case is mentioned, in which a man, far advanced in consumption, with an enormous cavity in one lung, and suffering from hectic, persisted in working in the caisson, contrary to the advice of Foley, and at the end of two months had gained very much in flesh, was looking well, and feeling in the best of health.

I shall have occasion hereafter, when treating of the Caisson Disease, to refer more in detail to some of the experiences of this writer.

In the year 1868 there was begun at St. Louis a work which involved the application of compressed air on a scale far exceeding anything before attempted. This was the sinking of two piers and two abutments for a bridge across the Mississippi. The magnitude of the work consisted in the great depth to which it was necessary to sink the caissons, in order to obtain a solid foundation. One of them, at the moment when it touched the rock, was 110 feet below the surface of the water. This implied a pressure within the caisson of 50 lbs. to the square inch. The dimensions of the caissons, too, far exceeded those of any before constructed, the average superficial area being about 3,700 square feet.

A large number of workmen were employed, and an opportunity was presented for studying the effects of compressed air upon the human body on a scale which dwarfed all former experiences into comparative insignificance.

The physician in charge was Dr. A. Jaminet, whose report is extremely interesting.* It describes a number of valuable experi-

* Physical Effects of Compressed Air. St. Louis, 1871.

ments upon the boiling point of water at various pressures, electrical phenomena, etc., and proceeds to detail the physiological action of high atmospheric pressure as demonstrated upon himself and others. The writer then gives his own experience in an attack of paralysis resulting from a prolonged sojourn in the caisson— a paralysis from which he fortunately recovered by the following day.

He next discusses the mode in which the pressure acts to bring about the morbid phenomena observed, and arrives at the conclusion, which the facts do not seem to me to warrant, that the ill effects are simply the result of exhaustion from too rapid tissue-change, caused by the absorption of an excess of oxygen. Following out this idea, he lays down a plan of treatment which consists simply of rest in a recumbent position, with the feet elevated, and the administration of stimulants and nourishment.

He describes, more or less in detail, seventy-seven cases, in eight of which death took place. The post-mortem appearances in these are described. They were all characterized by congestion of the brain and cord, and of most of the abdominal viscera.

Dr. Jaminet's observations are exceedingly valuable: but some of his conclusions seem to have been arrived at without sufficient thought. It is especially to be regretted that his theory of exhaustion, framed at the outset, prevented the trial of remedial plans other than the routine administration of stimulants and beef-tea.

The facts observed by Dr. Jaminet will be frequently referred to in the following pages, care being taken to give him credit for all that had not been anticipated by others.

CHAPTER SECOND.

THE NEW YORK CAISSON.

Before the St. Louis Bridge was projected, a much more gigantic work had been inaugurated at New York, and plans and specifications had been adopted which anticipated the leading features of the work at St. Louis. To cross a stream 1,600 feet in width with a single span was an idea never before entertained. But the difficulties were immensely increased by the fact that the towers to support this immense structure had to be erected under circumstances that rendered the usual methods for sinking piers impracticable. It was, therefore, determined to employ the method by compressed air, and caissons were constructed having the horizontal dimensions of the proposed piers, which, on the New York side, were 102 by 172 feet. Each caisson was in effect a wooden box turned bottom upward, the interior space being 9 feet high. The roof of the New York caisson (bottom of the box) was 22 feet thick, of solid timber bolted to-

gether, and was supported by frames running from side to side, which frames, together with the edges of the box, were to sustain the vast superincumbent weight, aided by the upward pressure of the condensed air within the caisson. The area of the structure was equal to seven building lots of 25x100 feet each.

The caissons having been built on ways, were launched in the same manner as a ship, and were towed to the points where the piers were to be located. Courses of granite blocks were then laid upon the top of the caisson, by which it was sunk until it rested upon the bed of the river. Air was then forced into the chambers beneath by means of engines upon the shore, until the water was entirely displaced, and the river-bed left dry. The pressure was maintained at this point, the engines working day and night. The workmen obtained access to the chamber by means of two shafts which extended above the surface of the water. At the bottom of each shaft were two air-locks, which were simply ante-chambers constructed of iron, into which the men entered from the shaft, and, closing an air-tight door behind them, admitted the compressed air from the caisson by means of a cock, until the pressure in the lock reached the same degree as that in the caisson, when a communicating door was opened, and the men passed into the chamber below. In going out, the process was reversed, the compressed air in the lock being allowed to blow off through a cock into the open shaft. The control of these cocks was intrusted to men detailed exclusively for that work, and upon their proper management depended the comfort, if not the life, of every one in the lock.

By a very ingenious arrangement, which it is not necessary to describe here, the earth excavated from beneath the caisson was carried up to the surface without affording opportunity for the air to escape. In this way the earth was being constantly removed from underneath the caisson, and the vast mass settled day by day down through the gravel and quicksand, which formed the bed of the river, until at a depth of 78 feet on the New York side, a solid foundation was reached. In proportion as the caisson settled the masonry upon it was built up, so that the top of the stone-work was always above water. When a solid foundation had been reached, the interior of the caisson was filled with concrete, and the 400,000 cubic feet of timber was left buried nearly 80 feet below the surface, where, practically indestructible, it remains as the foundation of the tower.

Of course the pressure of air required to keep the water out of the caisson increased in exact proportion to the depth. Thus, at the beginning of the work, the caisson being covered by forty feet of water, the pressure was about eighteen pounds to the square inch, while at the close of the work it stood at thirty-six pounds.

The air-locks were connected with the surface of the pier by means of a spiral stairway within the shaft. Ascending this was found to be exceedingly fatiguing as the depth increased, and the stair in one of the shafts was finally replaced by a steam elevator.

Looking upon it merely from a sanitary point of view, I regard it as a serious mistake to have placed the air-locks at the bottom instead of at the top of the shafts, as by that arrangement the men were compelled to make a fatiguing ascent at the moment when the circulation was embarrassed and the system unstrung by the sudden removal of the pressure. All testimony is agreed upon the ease, on the one hand, with which exertion is supported while in the compressed air, and upon the unfitness of the system, on the other hand, to bear even the slightest fatigue during the period immediately following the change to the normal atmosphere. These considerations should render the rule invariable that the air-lock is to be placed at the top of the shaft, unless an elevator is employed. In this view I am sustained by all the engineers connected with the work.

The caisson was lighted by gas supplied by means of a force-pump. The combustion of the gas, together with the breathing of the workmen, gave rise to the formation of a large quantity of carbonic acid. It soon became evident that the amount of air which was required to supply the leakage and keep up the requisite pressure was not adequate to maintain a healthy standard of purity in the air respired. This conclusion, arrived at by observation and calculation, was confirmed by trial. A rough, but satisfactory, test was supplied by taking a bottle of lime-water into the caisson and passing the air through the water by means of an ordinary flexible rubber syringe. It was found that a few compressions of the bulb were sufficient to give the water a decidedly milky hue. This method has the advantage over that employed by Dr. Jaminet, viz., merely shaking an open bottle containing lime-water—that it constantly brings new portions of air into contact with the fluid.

By increasing the number of compressors by which the air was supplied, (the excess of air escaping beneath the edge of the caisson,) the atmosphere was brought to such a degree of purity as to contain only one-third of one per cent. of carbonic acid, as I determined by actual analysis. This amount of vitiation was found not to affect the men unfavorably. To maintain this standard, however, nearly 150,000 cubic feet of air were required per hour.

The number of men employed at one time in the caisson varied from fifty to one hundred and twenty-five in the day time, and from fifteen to thirty during the night. At first the time was divided into two "shifts" of four hours each, separated by an interval of two hours. As the depth increased the hours were reduced, until at last

the two shifts comprised but four hours, divided by a four hours' interval.

It was not until the pressure had reached about twenty-four pounds that any serious effect upon the men was observed. At this time I began my daily attendance of from one to three hours at the bridge. The first step was to prepare a set of printed rules, copies of which were posted conspicuously. These rules were as follows:

- 1st.—Never enter the caisson with an empty stomach.
- 2d.—Use as far as possible a meat diet, and take warm coffee freely.
- 3d.—Always put on extra clothing on coming out, and avoid exposure to cold.
- 4th.—Exercise as little as may be during the first hour after coming out, and lie down if possible.
- 5th.—Use intoxicating liquors sparingly ; better not at all.
- 6th.—Take at least eight hours' sleep every night.
- 7th.—See that the bowels are open every day.
- 8th.—Never enter the caisson if at all sick.
- 9th.—Report at once at the office all cases of illness, even if they occur after going home.

I next subjected all the men to an examination intended to exclude all who were suffering from heart or lung disease, and those enfeebled by age or intemperance. All new men thereafter were required to present a permit signed by me before they were allowed to enter the caisson. Though but few were actually rejected, the knowledge that they would be examined, doubtless deterred many who were not sound from applying for work. The *personnel* was therefore of the best, as it then appeared. Subsequent experience would, however, have modified my choice materially.

On my recommendation a cup of good coffee was served to each man immediately upon leaving the caisson. It appeared to relieve, in a measure, the nervous prostration which marked the return to the open air : and possibly, by the effect which coffee is known to have, it may have done something, also, to check the tendency to too rapid tissue-change.

A large room in the yard was fitted up with bunks and benches, which afforded the men an opportunity of resting while the changes were going on in the system which were required to bring it into its normal condition after coming up. Connected with this room were conveniences for hot and cold bathing, and also lockers in which each man kept a change of dry under-clothing, to be put on immediately

on coming up. Each man was supplied by the company with a pair of long rubber boots, which were rendered necessary by the work requiring them to stand more or less in the water.

The physical conditions to which the men were subjected in their work were very peculiar. In the first place, in passing through the lock in going down, there was a very sudden rise of temperature from the condensation of the air. This rise amounted to upwards of 30° F. in many cases, and not infrequently, when the outside temperature was low, to 50° or 60°. This change in the temperature was coincident with an increase of atmospheric pressure of from 18 to 36 lbs. to the square inch. At the same time the men passed from an atmosphere of the usual dryness to one saturated or super-saturated with moisture. The labor required in the caisson was not unusually severe. After from two to four hours passed in the compressed air, the men repaired to the locks, where in the space of from seven to fifteen minutes the pressure was reduced to the normal standard. As the result of the expansion of the air in the lock, the temperature fell as rapidly as it rose in the former case. This, which was felt to be a serious inconvenience in the Brooklyn caisson, was remedied on the New York side by surrounding the interior of the lock with coils of pipe heated by steam. The steam was shut off at all times except while locking out.

The moisture of the atmosphere of the caisson, referred to above, was caused partly by the "water-packing" used in the condensers which supplied the air, and partly by the water with which the soil underneath the caisson was saturated.

From the 25th of January, 1872, when I assumed medical charge of the men, until the 31st of May, when I resigned the position, 110 cases of sickness occurred which were fairly due to the compressed air, and were of sufficient severity to come under treatment. Of these, *three* proved fatal.

The sick were treated in the first instance at the yard, where a room was set apart as a temporary hospital. Cases occurring during my absence were treated by the engineer on duty, according to a specified plan; or, if the case was severe, I was summoned. Serious cases were ultimately sent to the public hospitals or to their homes.

The ages of the men ranged from 18 to 50. They were of almost all nationalities, but I did not find that any sensible difference in ability to bear the work resulted from nativity, as observed by Pol.

The habits of many of the men were doubtless not favorable to health, but everything which admonition could do, was done to restrain them from excesses. Many of them slept in crowded lodging-houses, where the beds or bunks were arranged in tiers, one above

the other ; in rooms in which there was scarcely an attempt at ventilation. One of them fell a victim to spotted fever, contracted from such surroundings, and his death was at once ascribed by his comrades to the effects of the condensed air.

Serious inconvenience was occasioned to the men in the caisson by the large amount of unconsumed carbon from the gas, which floated in the air in the form of smoke. The inhalation of this produced more or less irritation of the air-passages, and gave rise to a very characteristic black expectoration. This continued for an astonishingly long period after the work in the caisson was terminated. At the time of my writing, nearly six months after the work was completed, some of the men are still coughing up sputa, streaked with black. Where this carbon could have been lodged for so long a period, is a question which I am not prepared to answer.

The smoking of the gas was found by some experiments of Mr. Collingwood, one of the engineers, to be due to the comparative immobility of the compressed air, which prevented the formation of the currents necessary to bring new supplies of oxygen to the flame. By reducing the aperture of the burners, and at the same time giving it such a form that the gas escaped in a thin sheet, a relatively greater surface was secured for contact with the air. This obviated almost entirely the tendency to smoke, and added also to the illuminating power of the gas.

The sinking of the caisson was begun on the 12th of December, 1871, and the filling in with concrete was completed on the 20th of July, 1872 : the duration of the submarine work being 221 days.

During this period I was in the habit of frequently entering the caisson, remaining from one to two hours at a time. Yet in my case, with the exception of occasional slight pain in the maxillary sinuses, not the least inconvenience was experienced.

CHAPTER THIRD.

EFFECTS OF COMPRESSED AIR.

The effects of a highly condensed atmosphere upon the system may be divided into those which are physiological or consistent with health, and those which are pathological, and constitute or induce disease.

The physiological effects will be considered according to the organs or functions in which they are exhibited.

Effect on the Hearing.—It is a law of acoustics that within the limits of mobility the denser the medium through which the sound waves are communicated, the larger the wave, and therefore the

louder the sound. This supposes, of course, that the ear itself remains under normal conditions. Such, however, is not the case when the observer is in a highly condensed atmosphere. The unusual pressure upon all parts of the auditory apparatus opposes a mechanical obstacle to the freedom of vibration, which is essential to perfect hearing*. Hence, although larger sound waves may strike upon the ear-drum, feebler impressions are communicated to the auditory nerve, and the sound appears to be fainter than in the open air. Thus, by repeated experiments, I found that a watch that could be heard distinctly at a distance of 18 inches in a very noisy place in the open air, could not be heard at a greater distance than two inches in the comparative silence of the caisson.

At the same time the *velocity* of the waves of sound is greater, and hence the *pitch* is higher. A deep bass voice is changed to a shrill treble, and the prolonged, heavy sound of a blast is so modified as to resemble the sharp report of a pistol.

This modification of sound is very striking, and is almost the only thing to remind the casual observer that he is moving about in an atmosphere three or four times as dense as that to which he is accustomed.

A curious fact, noticeable under these circumstances, and one which was long ago observed in diving-bells, is that it is impossible to whistle. The utmost effort of the expiratory muscles is not sufficient to increase materially the density of the air in the cavity of the mouth, and hence on its escape there is not sufficient expansion to produce a musical note. A similar difficulty, though in a less degree, is experienced in speaking, and for this reason protracted conversation is very fatiguing.

Effect upon Respiration.—In a highly compressed air, the frequency of the respiration is increased. Dr. Jaminet gives the rate as 21 per minute, with a pressure of 33 lbs., which accords with my own observations. He ascribes this increase of three or four per minute to an increased absorption of oxygen. Experiments show, however, that simply increasing the supply of oxygen, *diminishes* the frequency of respiration instead of increasing it. The true explanation, I think, is to be found in the fact that the quantity of carbonic acid held in solution by blood, as by water, is in proportion to the pressure to which the gas is subjected; and hence with the pressure existing in the caisson, the elimination of carbonic acid from the blood would not be as perfect as under normal circumstances, unless the air in the lungs were more frequently changed. As observed by Francois and Dr. Jaminet, the depth of the inspirations is also increased. With

* An analogous fact was observed by Foley, viz., that his watch invariably *lost time* when taken into the caisson, thus showing that the movements of the balance-wheel were less free in the compressed than in the normal air.

the view of appreciating the amount of increase of the respiratory movements, as well in amplitude as in frequency, I devised the following plan: By a very simple contrivance attached to a steel band placed around the chest, a measuring tape was made to traverse with each inspiration a distance corresponding to the increase in the circumference of the chest. The aggregate distance traversed in a given time was made the standard of comparison, and of course indicated the combined frequency and amplitude of the respirations.

A number of trials with this instrument made upon myself in the open air, gave a very uniform result of $1\frac{1}{2}$ inches of tape unwound every two minutes. On repeating the experiment in the caisson under a pressure of 33 lbs., $2\frac{3}{4}$ inches were unwound in the same time.

Effect upon the Circulation.—It has been shown by numerous observers that under a slightly increased pressure, such as is employed in compressed air-baths, the pulse loses in frequency from the first. This is doubtless due to an increased absorption of oxygen by the blood, which thus affords a sufficient supply to the tissues without the necessity of keeping up the usual activity of the circulation. In the course of some experiments undertaken nearly four years ago, I demonstrated that the same effect results under a normal pressure from adding oxygen to the air inhaled. But as the pressure increases, the question is transferred from the domain of chemistry to that of mechanics. The condensation of the tissues from the pressure to which they are subjected, and the consequent narrowing of the vessels, oppose a physical obstacle to the circulation, which is felt before the blood has time to become surcharged with oxygen, and while there is still a necessity for an active circulation. The labor of the heart is thus increased, and its action, in consequence, excited. I have frequently seen the pulse rise to 120 immediately upon entering the caisson, where the pressure was from 30 to 35 lbs. to the inch.

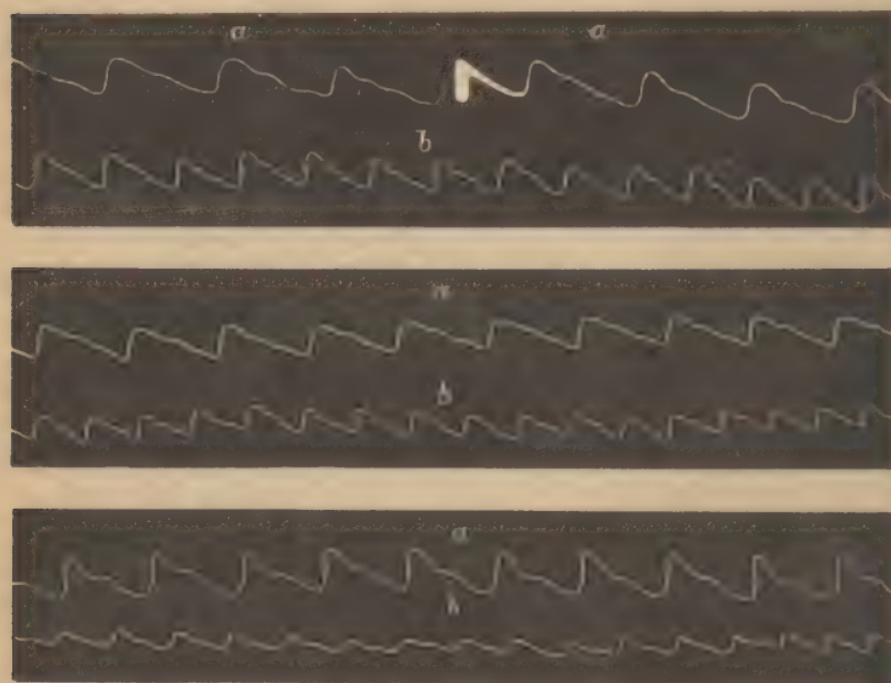
But after the lapse of a period varying in different cases from half an hour to two hours, the pulse falls back to its normal standard, or even, it may be, below it.* The blood has now become saturated with oxygen, and consequently a less active circulation is demanded.

Doubtless, if the pressure were very gradually admitted, the preliminary rise in the pulse would not take place, the favorable chemical action keeping in advance of and counteracting the unfavorable mechanical conditions.

The effect of high atmospheric pressure upon the *volume* of the pulse is always, according to my observation, to diminish it. This is easily accounted for by the pressure exerted upon the artery, which prevents its yielding readily to the expanding force of each successive

* My experience in this corresponds precisely with that of Dr. Jaminet.

wave of blood. Hence the pulse is small, hard, and wiry. These characteristics are independent in a great degree of the frequency of the beat, although as the heart recovers from the irritable condition into which it is thrown by the sudden increase of the pressure, and settles down, so to speak, more calmly to its work, it contracts with more force, and the pulse gains somewhat in volume. These changes in both the frequency and fullness of the pulse are well shown in the annexed tracings, taken in the Brooklyn caisson. The upper line represents in each case the normal pulse, the lower line that in the compressed air.



The difference in the readiness with which the process of adaptation to an increased pressure is accomplished in different persons is shown by the pulse-rate of eleven men taken an hour and a half after going into the caisson when the pressure was thirty-five pounds. The figures are arranged in the order of frequency.

116—116—106—104—96—92—88—76—74—68—52.

These figures give an average of ninety. On another occasion, with a pressure of thirty-two pounds, and a sojourn in the caisson of two and a half hours, the average was eighty. Whether a longer exposure to the same pressure would have produced a further decline in the frequency of the pulse is a question which the hours for working did not allow me to determine.

It is remarkable that the wide variations in the pulse-rate above mentioned were not accompanied by any symptoms appreciable to the individual. A man with a pulse of fifty-two, and another with one of one hundred and sixteen, felt equally well, and each was entirely unconscious of anything unusual in the heart's action.

The effect of the pressure upon the cutaneous vessels is shown by the pallor of the face, which is very marked, and continues for fifteen or twenty minutes after leaving the caisson. The hands, too, feel shrunken, and the palmar surface of the fingers is often shrivelled, as if soaked in water. The pressure acting upon all sides of the fingers empties them to a considerable extent of blood, rendering the skin apparently too large for them. The veins, too, on the back of the hand seem to be effaced.

This absence of blood from the surface implies necessarily an excess in the interior of the body, where the effect of the pressure is not as great. This point will come up again in considering the pathology of the Caisson Disease.

Effect upon Temperature. In none of the reports upon the effects of high pressure as employed for engineering purposes, have I been able to find any records of temperature. J. Lange,* however, found that under the comparatively slight pressure which is used as a remedy, the temperature of the body suffered a slight decrease. This is, no doubt, due to an increased absorption of oxygen, which has been shown by Mr. Savory and also by experiments of my own to produce this effect.

During the work in the New York caisson when the pressure was about 32 lbs., I took the temperature of seven of the men an hour and a half after entering the caisson, and found that it averaged 99.6° F., exactly one degree above the normal standard. At first I accepted this as the result of the increased interstitial change so strongly insisted upon by Dr. Jaminet, but subsequent observation led me to interpret it differently.

The temperature of the body in health is kept at about 98.6° F., by the constant evaporation from the surface. But in the caisson, as already mentioned, the air was always nearly or quite saturated with moisture, so that evaporation from the surface must have been practically suspended. With the temperature of the air at 76°, as it was at the time of the observations, and the men engaged in severe labor, it is easy to see how the absence of the cooling process of evaporation from the surface would lead to a rise of one degree of the thermometer. This view is strengthened by the result of three observations on a subsequent occasion, when the temperature in the caisson stood at 81°, instead of 76°. The average in this instance was 101°.

* Vivenot.

A rise of five degrees in the temperature of the air could not sensibly affect the rapidity of tissue-change, but if not counteracted by evaporation from the skin, it would soon tell upon the temperature of the body.

The influence of the hygrometric condition of the atmosphere upon the temperature of the body is a matter of daily observation. On a clear, dry day, with a high barometer, we are surprised to find the thermometer indicating a temperature much higher than our sensations would lead us to expect, while on the contrary, on a cloudy day, with a low barometer, we can scarcely persuade ourselves that the temperature is not many degrees higher than the thermometer indicates. In the dry, clear air of New Mexico I have supported a temperature of 110° , without inconvenience, while in the humid atmosphere of the Florida Keys I have found it almost unbearable at 86° .

Effect upon the Perspiratory Function.—Several writers have observed that it is immediately remarked by every one entering a caisson that the secretion from the skin is apparently immensely increased. It is noticeable even when the temperature of the air is moderate, but as this increases it becomes a very serious annoyance. The clothing quickly becomes saturated, which, besides the discomfort it occasions, exposes to great danger of taking cold on going out into the open air.

But a little examination served to show me that in the New York caisson, at least, there was really no increase of the secretion from the skin, but that, instead of evaporating, the moisture accumulated upon the surface, and thus simulated excessive sweating. This was owing to the moist condition of the atmosphere already mentioned, which rendered the drying of the surface by evaporation impossible. The atmosphere possessed to an extreme degree the quality of "mugginess," and the apparently profuse perspiration was merely an exaggeration of what we suffer from in very damp weather, even though the temperature be not extreme.

So far from the perspiratory glands being stimulated by the density of the atmosphere, it is probable that the anæmia of the skin already described, as resulting from the pressure upon the surface, would tend to lessen the secretion by diminishing the supply of blood to the glands.

That there is not an undue amount of fluid carried off through the skin, is shown by the absence of thirst so generally remarked.

The foregoing explanation of the apparent increase of perspiration is important, as it bears upon the theory of excessive waste of tissue, in which the perspiration is supposed to aid.

Effect upon Digestion.—Nearly all authors who have written upon the effects of compressed air agree in stating that for a time, at least,

it increases the appetite to a remarkable extent. Indeed this is one of the first and most favorable results observed where compressed air is applied remedially. With this experience my own observations in the main agree. It was frequently remarked by the men working in the New York caisson that their work made them unusually hungry, that they "could not get enough to eat," etc. Of course, it was not possible to obtain any exact data as to the relative amount of food consumed, but from careful inquiries I arrived at the conclusion that it was considerably in excess of what is usual in the case of men engaged in similar labor in the open air. Still, there were many exceptions to the general rule, especially among those who had been long engaged upon the work, and whose general tone was beginning to deteriorate. Among these, loss of appetite was often complained of.

The fact of this generally increased appetite seems to point to an increased waste of tissue, to be supplied by a greater consumption of food. An increased absorption of oxygen such as we assume to take place, seems from the observations of several authorities* to imply greater activity of tissue-change as the *ultimate* result. But in this case I think it is scarcely safe to accept this explanation at once as conclusive and sufficient. It may well be questioned whether during the actual sojourn in the caisson the functions of digestion, absorption, and assimilation proceed normally under the wide departure of the system from its natural conditions. If it could be shown that a considerable portion of the food taken before entering the caisson is but imperfectly digested or assimilated, the subsequent hunger would be readily accounted for. I am not aware that this point has ever been investigated, but I can scarcely believe that such an increase of appetite as is described could depend wholly upon increased interstitial change without giving rise to marked elevation of temperature and other symptoms denoting unusual chemical activity. On the contrary, I think it highly probable that an examination of the dejecta would show them not to be entirely exhausted of nutritious material. At all events, until this point is subjected to rigid tests, it will be unsafe to regard the amount of food consumed as a measure of the metamorphosis of tissue.

If the metamorphosis of tissue is really greatly accelerated through the influence of compressed air, it should be apparent in a more prompt healing of wounds. The following experiment was intended to test this point:

Four pigeons were selected, as much alike as possible in size and vigor. Under the wing of each a wound was made by removing a circular piece of the integument about half an inch in diameter. Two of the pigeons were then sent down into the caisson, the other

* "New York Medical Journal." April, 1870.

two being retained in the hospital on the wharf. The conditions in other respects were the same. At the end of six days the wounds in the two below were perfectly healed. Of the two above, in one the wound was perfectly healed, while in the other it was still covered by a scab, which fell off two or three days later.

The result of this experiment would not indicate any considerable difference in the activity of the vital processes. I may remark that the workmen never spoke of the wounds or injuries they received as healing more rapidly than when working in the external air.

Effect upon the Urinary Secretion.—Dr. Jaminet, in his observations at St. Louis, found that the amount of fluid secreted by the kidneys was very much increased, in some instances nearly doubled, while the specific gravity was but little, if at all, below the usual average. This shows that the solid matter excreted was also in much greater quantity than usual.* But I cannot agree with him in attributing this exclusively to the excessive waste of tissue from over-oxydation of the blood. The explanation is to be found, I think, chiefly in the fact that the skin, as already stated, performs its function very imperfectly, owing to the impossibility of evaporation from the surface when the air is already loaded with moisture, and hence a portion of its duty is forced upon the kidneys, organs always ready to act vicariously for the skin or the mucous surfaces.

Furthermore, the excretion of a large amount of urea indicates a relatively *deficient* oxydation of tissue, and is one of the characteristics of those diseases in which respiration is suddenly embarrassed, as, for instance, pneumonia.

Another circumstance not to be lost sight of, is that the pressure upon the surface acts mechanically to congest all the abdominal viscera, and that congestion of the kidneys, within physiological limits, produces increased secretion of urine.

From what precedes it will be inferred that I am not willing to accept the view which practically sets no limit to the amount of oxygen that the system will appropriate in a sufficiently condensed atmosphere. Even if absorbed by the blood, it does not follow that the excess of oxygen is received into the normal vital relations with the tissues. It may be held in simple compulsory solution in the blood, as in any other liquid; it may even give rise to chemical changes in the blood, and solid tissues as in dead matter, and thus act as a poison, as asserted by M. Bert.† but we have no warrant for believing that it so acts as to cause the removal of particles not yet effete, and which but for this would have remained normal active constituents of the

* These observations accord with those of Foley, J. Lange, Pol, Pravaz, and others.

† L'Institut, July 3, 1872

body. Behind mere chemical action lies a vital principle in accordance with which each molecule is born, as it were, into the economy, reaches maturity, performs its function, becomes effete, and is succeeded by a new molecule: and to break in upon this order is to strike at the very essence of life.

I do not intend by this to deny that an atmosphere highly oxygenated, either by the addition of oxygen or by compression, is capable of accelerating the vital processes within certain limits. I only contend that these limits correspond with the extreme limit of *physiological* demand—that the capacity of the system to appropriate and use oxygen has a definite relation to the possible wants of the system *under natural conditions*. For a contingency beyond these, nature has made no provision.

CHAPTER FOURTH.

PATHOLOGICAL EFFECTS.

The pathological effects of high atmospheric pressure comprise certain phenomena easily explained upon mechanical principles, and in addition to these, a group of symptoms, having a definite relation to each other, and constituting a specific affection, which, from the peculiarity of its origin, I propose to call the *Caisson Disease*.

The affections, which are of a purely mechanical nature, relate to the cavities communicating with the nasal passages, such as the ears and the frontal and maxillary sinuses, etc.

Affections of the ears are mentioned by nearly every writer on the subject of compressed air, and are extremely common. They depend, for the most part, upon closure of the Eustachian tubes, by which communication of the cavity of the middle ear with the external air is cut off. The men under my charge were warned most strenuously not to go into the lock unless they were able, when holding the nose and blowing forcibly, to feel the air enter both ears, thus insuring that the tubes were pervious. Nevertheless, cases often occurred in which this precaution was neglected, and the individual was, as a consequence, "caught in the lock," unable to "change his ears." This inability to equalize the pressure upon the two sides of the ear-drum, caused extreme pain, and sometimes entailed serious results. The effect is two-fold. The pressure upon the outside of the drum being greater than upon the inside, the membrane is pressed inward with a force, which, if it does not produce a rupture, at least causes a degree of tension which so delicate an organ as the ear is not fitted to bear with impunity, and which may be the starting point of an acute inflammation. (See Case I., p. 43.)

But the pressure may be so great as to rupture the drum at once, as in Case II., p. 43.

When there is continued exposure to the effect of compressed air, with closure of the Eustachian tube, the structures within the cavity of the tympanum not being acted upon by the increased pressure, are placed relatively in the same position as the skin under a cupping-glass, and the same result follows, viz., intense congestion, which may, in this case, lead to inflammation. Indeed, the difference in pressure within and without is much greater than in the case of the cupping-glass, since in the latter it cannot exceed one atmosphere, while in the former it may be two or three atmospheres.

The stoppage of the Eustachian tube may very frequently be overcome by forcing in air through the nose after the method described by Politzer. In this way a great many of the men under my care were enabled to continue their work, who otherwise could not have done so, without incurring serious risk. This simple operation was constantly called into requisition, as many as four or five of the men sometimes presenting themselves in the course of my visit to have their "ears blown out," and it rarely happened that they experienced any difficulty afterward on entering the lock.*

Three cases of extreme deafness came under my notice, two of them in laborers, and one in the person of a gentleman, who was advised by a physician to visit the caisson with the hope that he might receive benefit from the action of the compressed air. In all these cases the hearing was very much improved while in the caisson, but on returning to the open air the former degree of deafness immediately returned.

A number of cases of otitis are mentioned by François, as occurring under his observation during the sinking of the caissons at Strasburg.† His favorite remedy was oil of jasmine dropped into the ear. He also employed leeches and fomentations. He condemns catheterism of the tubes, on theoretical grounds, while admitting that he had never employed it.

Pain, more or less severe, in the frontal or maxillary sinuses was sometimes experienced. This was doubtless caused by a temporary closure of the passage leading to the nasal cavity. In one case, in which the frontal sinus was affected, the pain, though not severe, was very persistent, continuing for several days.

In one case pain in the frontal sinus was felt as the pressure was increasing in the lock, and again, and more severely, as the pressure was reduced in returning to the open air. This latter pain was accompanied by a discharge of bloody mucous from the nose. In this case there was doubtless closure of the passage into the sinus, thus

* I am under obligations to Dr. Roosa for valuable hints in reference to the treatment of these cases.

† See page 9.

preventing the equalization of the pressure, and giving rise to the pain first felt. There resulted also congestion of the lining membrane, followed by an increased flow of mucous and extravasation of blood. But in the course of the two hours passed in the caisson, the air gradually filtered through the obstruction, and when the outside pressure was removed, the air thus imprisoned forced a way out, carrying before it the mucous and blood that had accumulated in the sinus. (See Case IV., p. 43.)

It becomes an interesting question what degree of condensation of this atmosphere will prove directly fatal. Dr. Richardson, of London, told me recently that he had experimented largely upon this subject, and that for the small animals which he had employed, such as rabbits, cats, dogs, etc., the limit of endurance seemed to be between six and seven atmospheres. He found, however, that the result varied widely, with comparatively slight variations of temperature, such as would have no appreciable effect upon vitality under other conditions.

CHAPTER FIFTH.

THE CAISSON DISEASE.

DEFINITION. --*A disease depending upon increased atmospheric pressure, but always developed after the pressure is removed. It is characterized by extreme pain in one or more of the extremities, and sometimes in the trunk, and which may or may not be associated with epigastric pain and vomiting. In some cases the pain is accompanied by paralysis more or less complete, which may be general or local, but is most frequently confined to the lower half of the body. Cerebral symptoms, such as headache and vertigo, are sometimes present. The above symptoms are connected, at least in the fatal cases, with congestion of the brain and spinal cord, often resulting in serous or sanguineous effusion, and with congestion of most of the abdominal viscera.*

SYMPTOMS.

Neuralgic Pains. These constitute in general the first and most characteristic symptoms, and are very seldom absent. The accession is often very abrupt, as if the patient "had been struck by a bullet." At other times the pain is slight at first, but rapidly increases in intensity. In well-marked cases the suffering is extreme, men of the strongest nerve being completely subdued by it. It is "as if the flesh were being torn from the bones." The pain is usually of a remittent or paroxysmal character, the exacerbations occurring at short intervals, especially if the patient attempt to move. Though usually designated as "cramps," these pains are rarely accompanied by muscular spasms. They generally begin in one or both of the

knees, shifting to the legs or thighs, and then perhaps creeping up along the trunk to seize upon the shoulders and arms. Not unfrequently the severest pain is felt in the spine, and especially in the lumbar portion. There is usually some degree of tenderness with the pain, so that the patient will complain if friction be applied too vigorously. There is also a painful stiffness in the affected limbs, that precludes motion in the absence of actual paralysis.

In some cases, there are swelling and heat as well as tenderness, indicating engorgement of the tissues, and this may persist for several days, being followed occasionally by discoloration, as if from a bruise. (Case VII., p. 44.)

François mentions a case in which the engorgement was followed by suppuration. In two of my cases, minute spots of extravasated blood in the substance of the skin at the seat of pain, gave the surface the appearance of being spattered with red ink. (Case XI., p. 45.)

A curious case of the swelling of the mammary gland recurring each day is given among the Illustrative Cases, No. IX. François relates a similar instance.

The Pulse.—At the outset of the attack the pulse will differ according to the time which has elapsed since leaving the caisson, being, as a rule, quicker and more frequent in proportion as the time is shorter. Dr. Jaminet observed that if the attack occurred immediately after coming up, the pulse usually ranged from 95 to 115, while, if it were delayed for half an hour, the pulse would be slow—perhaps as low as 60.

But as these rates do not differ from those in healthy persons at the same periods after leaving the caisson, they do not possess any special significance in those taken sick.

The subsequent character of the pulse is simply indicative of the general condition of the patient.

The Skin is usually cool at first, often of a slightly leaden hue, and nearly always covered with a profuse cold perspiration, standing out in beads upon the surface. This perspiration is very characteristic. At first I supposed it to be owing to the excessive pain which the patient was suffering: but subsequently it occurred in several cases in which the pain was slight or entirely absent. (See Case VI.) I was, therefore, inclined to attribute it to a relaxation of the cutaneous capillaries through some nervous agency analogous in its action to what we see in cases of extreme terror, and having its origin in the general disturbance of the nervous system which characterizes the disease.

In several instances in which I ascertained the *temperature* in the axilla, it was found to be normal.

Epigastric Pain and Vomiting.—Pain at the pit of the stomach, usually, but not always, attended by vomiting, is of frequent occurrence. It occurred in 24 per cent. of my cases. This is a much smaller percentage than that observed by Dr. Jaminet, who found the gastric symptoms to be present in 66 out of 77 cases. This may be owing to the pressure being greater at St. Louis than at New York, nearly all of Dr. Jaminet's cases occurring under a pressure of 40 lbs. and upward, while the pressure at New York did not rise above 36 lbs.

The pain in the epigastrium, if not relieved by treatment, is generally followed within a brief period by vomiting, which may continue with great persistence even after the pain has ceased. In most cases, however, the vomiting is limited to the ejection of the contents of the stomach.

In a few instances I observed the occurrence of vomiting without the usual preceding pain. In these cases there was also dizziness, indicating that the vomiting was of cerebral origin.

Paralysis—This occurred to a greater or less degree in 47 out of 77 cases observed by Dr. Jaminet. This is at the rate of 61 per cent. At New York it occurred in only about 15 per cent. of the cases; the difference being due, no doubt, to the difference of pressure. The paralysis affects most frequently the lower half of the body, but it may include the trunk or one or both arms. In rare instances the arms alone are affected. The paralysis usually comes on a short time after the beginning of the pains, but it may occur where there is very little if any pain. (Case XXV.) It affects sensation as well as motion. The patient does not, however, obtain relief from his suffering, since the pain in the limbs will continue after pain from other sources is no longer felt. Thus a leg, for example, may be entirely insensible to pricking or pinching, while at the same time it is the seat of extreme suffering. In fact, the neuralgic pain and the paralysis seem to be so far independent of each other, that either may exist separately as well as both together.

The degree of paralysis may vary from mere weakness of the limbs, with slightly impaired sensation, including a loss of "hold upon the ground" in walking, to complete loss of motion and sensation in the affected part. Even the minor degrees generally involve the bladder, and in two or three of my cases the paralysis, after the first day or two, was confined to this organ.

Cerebral Symptoms.—Symptoms of a transient character are often observed, which have their origin in the brain. They consist of headache, dizziness, double vision, incoherence of speech, and sometimes unconsciousness, the last from syncope. They are usually of very short duration, passing off in a few hours. In the fatal cases,

however, a condition of profound coma is the usual forerunner of death. The occurrence of this symptom leaves but little hope of the patient's recovery.

Prognosis.—The duration of the Caisson Disease varies from three or four hours to six or eight days. When paralysis takes place, this may continue for weeks, or it may pass off within twelve hours. The cases marked only by neuralgic pains do not generally last more than twelve hours, though some continue five or six days.

Death occurs only in cases which are severe from the first, and are marked by symptoms of serous or sanguineous effusion about the brain or cord.

Morbid Anatomy.—The constant lesion in fatal cases of Caisson Disease is congestion of the brain or spinal cord. This congestion may be evenly distributed, or it may vary in intensity in different localities. This is especially true as regards the cord. The congestion affects both the meninges and the substance of the brain or cord. In some instances extravasation of blood takes place, as in Case XXVI., chapter 6. In most of the published cases there was found also more or less serous effusion in the arachnoid.

The tissues of the scalp and those surrounding the spinal column are sometimes engorged. Dr. Jaminet describes a case in which the tissues over the spine were congested, the vascularity increasing regularly as the dissection proceeded deeper toward the vertebral column.

When sufficient time elapses before death, there may be softening of the brain, occurring in spots. This is probably due to occlusion of the vessels by coagula formed during the primary congestion.

Congestions also occur in other localities, and especially in the solid abdominal viscera. The liver and spleen have been found engorged in nearly every case. The kidneys, too, are usually congested, and in several cases described by Dr. Jaminet, clots of blood were found extravasated in the organ.

The mucous membrane of the stomach, intestines, and bladder is often found injected and marked with ecchymotic patches.

The lungs, in cases of true Caisson Disease, seldom present any other change than simple hypostatic congestion.

Pathology. It is probable that the pathology of this disease is not entirely uniform in all cases. Doubtless, the chief element in it is the congestions already described, and especially of the brain and spinal cord. The mechanism, therefore, of these congestions, becomes a subject of paramount importance.

It is obvious that if the blood were exposed to an equal pressure in all parts of the body, there would be no change in its distribution.

It is equally clear that the blood, if free to move, will pass from a place where the pressure is greater to one where it is less. The body is made up of structures of different densities, and presenting a varying resistance to compression. But permeating these structures in every direction are vessels in perfect communication throughout the entire system, and filled with a mobile fluid, which is free to change its locality in obedience to any force which is brought to act upon it. Now, when the surface of the body is subjected to an even pressure on all sides, the tendency is to a distribution of this pressure toward the centre. If the body were composed entirely of solids, this could be effected only by the compression of those solids, and a point would very soon be reached where the resistance would balance the compressing force, and the parts lying more toward the centre would remain unaffected. But the presence of a fluid in the structures, with free channels in which to move, changes all this. While the solid tissue resists compression, the fluid blood retreats from the surface to the centre, and accumulates there until an equilibrium of pressure is produced.

Hence we deduce the law, that under high atmospheric pressure the centres will be congested at the expense of the periphery.

But, aside from location, vessels coursing through dense and resisting organs, will be less exposed to external pressure than those passing through soft and yielding structures. Hence a second law, that firm and compact structures will be congested at the expense of those more compressible.

But there are structures very soft and yielding in themselves, yet enveloped in a rigid casing of bone which entirely shuts off the influence of external pressure. Hence the establishment of the equilibrium in them is wholly dependent upon an afflux of blood. This gives us the third law, that structures within closed bony cavities are congested at the expense of all others.

In accordance with these laws, we shall find that while in the caisson, the condition of the different parts in regard to the supply of blood will be as follows :

The skin and the superficial structures will be anaemic.* The central portion of the limbs and the interior organs of the body will be congested. The solid viscera of the abdomen will be especially engorged on account of both situation and structure. The brain and spinal cord, and the interior of the shaft of the long bones, will be congested to a high degree from the operation of the third law.

These changes are not perfected until a considerable time has been passed in the compressed air. The circulation up to this point goes on everywhere with vigor, the change being in the relative calibre of

* This is shown by the pallor which is very characteristic. See p. 21.

the vessels, not in their tension. The counter-pressure becomes uniform throughout the whole vascular system, but this counter-pressure supersedes the natural muscular resistance or *tone* of the vessels, which have become passive tubes. The blood is distributed not in accordance with the physiological demands of the different parts, but in obedience to overpowering physical force.

This is the condition of the circulation at the moment that the process of locking out begins. Yet the changes which have taken place up to this point are not the cause of the morbid phenomena which constitute the Caisson Disease, else the attack would take place while *in* the compressed air, instead of after leaving it. It is evident that the *removal of the pressure*, and not the pressure itself, is the immediate cause of the seizure.

This removal is effected in the few minutes which are occupied in locking out. But it is not to be supposed that the vessels will instantly assume their normal condition. They are in a state of relaxation, not only in the congested, but also in the anaemic parts: in the former, because of over-distension—in the latter, because the muscular coat cannot at once recover from its inaction. The aggregate capacity of the vascular system will, therefore, be in excess, compared to the volume of blood to be conveyed; or, in other words, there will be a lowering of vascular tension.

Hence, the circulation will be languid, and the congested parts will not readily empty themselves of the excess of blood which they contain. Especially will this be the case in the brain and spinal cord, where the conditions are most favorable for the production of congestion. The capillaries being clogged with effete blood, the nutrition of the part must suffer, and disturbance of function will result.

It is to this, I think, that the delirium, and the transient loss of consciousness, which occasionally occur, are to be attributed. When the spinal cord is the seat of this condition, pain in the parts deriving their nerves from that section of the cord may result, or paralysis more or less complete may follow.

This appears to me to account for the phenomena in those cases in which the local symptom is paralysis or pain of a transient or shifting character. These cases may, I think, be considered as entirely spinal in their origin. But in many cases there are evident local changes such as tumefaction, rise of temperature, etc., which indicate local irritation, and which are probably due to obstruction of the vessels of the part as a sequel to the local congestion. This explanation is applicable also to those cases in which the pain is fixed in one locality, which may be very much circumscribed, and where it persists for days without intermission, feeling, as the patient expresses it, "as if it were in the bone," where it very likely is. Such a pain presents a

marked contrast to those shifting pains which have been described, and if considered of spinal origin, would indicate a serious lesion confined to a minute portion of the cord. That such a circumscribed lesion might occur as a very rare exception, must be admitted; but that it should be present in a considerable proportion of cases is in the last degree improbable.

The testimony of all observers is, that the liability to attack is directly as the duration of the stay in the caisson. This admits of an easy explanation on the theory which I have advanced. The more thoroughly the system has become adapted to the change in the circulation, the less readily it will resume its normal condition when the pressure is removed. The congested vessels, especially, will lose their contractility in proportion to the time their muscular fibres have been upon the stretch.

It was suggested by François, that the morbid phenomena resulting from high pressures might be due to the liberation of air which had been absorbed by the blood while under pressure, but which was set free again when the pressure was removed.

The same idea has since been advanced by Prof. Rameaux, of Strasburg.

Within the past year M. Paul Bert has communicated to the French Academy* the results of a series of experiments made upon animals with very high pressures, reaching sometimes to 19 atmospheres. He shows that when death is the direct result of the pressure it is induced by an excessive absorption of oxygen, which then enters into chemical union with the blood, and acts as a poison. He found that the gas which escapes from the blood after the pressure is removed, is composed of a mixture of nitrogen and carbonic acid, with scarcely a trace of oxygen, the oxygen being retained by the blood. This poisoning by oxygen, however, produces its effect while in the compressed air, and therefore cannot be a factor in the production of the Caisson Disease.

But M. Bert re-asserts the theory of François and Prof. Rameaux, with this difference: that he claims that bubbles of *nitrogen* instead of air are the cause of the interruption of the circulation. These bubbles he has discovered after death in the vessels of the brain and cord. But he states that when the pressure does not exceed five atmospheres, three minutes allowed for the restoration of the normal pressure will be found to prevent the formation of these globules of nitrogen. Now, we find the Caisson Disease occurring when the pressure does not exceed two atmospheres, and when six to eight minutes are allowed for locking out. It would seem that under these conditions, the gas should escape through the lungs as

* Comptes Rendus, August, 1872, and February and March, 1873.

rapidly as it is disengaged from the blood. Moreover, we find that in the Caisson Disease the attack often comes on several minutes or even hours after leaving the compressed air. During this interval, if any free nitrogen were circulating with the blood, it should constantly become less by diffusion through the pulmonary membrane, and it is scarcely conceivable that if the quantity at the moment of emerging into the open air were not enough to produce obstruction of the circulation, such an effect could take place at a later period.

It is also very difficult to reconcile with M. Bert's theory the fact of the comparative immunity from danger which results from repeated exposures to the effects of compressed air. If the action be that of purely physical causes, habit could make no difference. The obstruction of the vessels described by Bert is a condition of which the system could never become tolerant by frequency of repetition. On the other hand, it is perfectly conceivable that vessels which are required to receive a varying quantity of blood at different times may acquire the power of more ready adaptation to these changes of quantity, since this is only an extension of the physiological principle which we see exemplified in all organs which have an intermittent function. Hence this objection, which lies against the explanation of M. Bert, does not apply to the views as to the pathology of the disease which I have advanced.

Thus, while recognizing the value of M. Bert's observations, I am still of the opinion that he is in error in applying them to the comparatively low pressures and gradual decompression which are consistent with the production of the Caisson Disease.

In order further to test this question, I performed the following experiment: The pressure in the caisson being about 35 lbs. to the square inch, a dog was sent down, and allowed to remain seven hours in the compressed air. At the end of that time I went down, and after killing the animal with prussic acid, I opened the vessels of the neck, and allowed four ounces of blood to flow into a six ounce vial. The space above the blood was then completely filled with olive oil, and a cork, pierced by one leg of a small U-shaped tube, was forced tightly into the bottle, displacing a portion of oil, which escaped through the tube. By this arrangement every particle of air was excluded from the apparatus, even the tube, which extended a little below the cork, being entirely filled with oil. The object of the oil was to avoid the difficulty which would arise from coagulation of the blood in the tube if blood only were employed.

The apparatus thus arranged was then taken into the open air. While passing through the lock five minimis of oil escaped from the tube, which amount was increased during the next half hour to eight minimis. The temperature of the caisson and that of the external

air were almost exactly alike, so that the result obtained could not be influenced by contraction or expansion due to temperature. The eight minimis, therefore, represented the bulk of air which was disengaged from the blood in consequence of the removal of the excess of pressure. This is only $\frac{1}{24}$ of the bulk of the blood experimented upon. Now the experiments of Demarquay* show that from 80 to 150 c. centimetres of oxygen can be thrown into the veins of a medium-sized dog in the space of four or five minutes, without producing serious consequences: and other observers have demonstrated that air slowly introduced into the veins escapes through the lungs, and that a large quantity can be injected in this way without danger.

Hence with the small amount of air which my experiment shows to be disengaged from the blood, and with the process extended over eight or ten minutes at least, it seems clear that we cannot explain in this way the phenomena observed in the Caisson Disease.

Causes.—The one essential cause, without which the disease can never be developed, is *the transition to the normal atmospheric pressure, after a prolonged sojourn in a highly condensed atmosphere*. Hence we have to consider two elements, *pressure* and *time*. As the momentum of a moving body is found by multiplying the weight by the velocity, so the danger in these cases is as the degree of pressure to which the person has been exposed, multiplied by the duration of the exposure.

But inasmuch as a prolonged sojourn in the caisson does not in every case produce the disease (many of the men employed escaping it entirely), it follows that there must be concurrent causes which determine its development. This is what we observe in many other diseases of a specific origin. Thus the essential cause of intermittent fever is exposure to a peculiar malaria, yet only a portion of those so exposed are affected by the disease.

The first of the concurrent causes of the Caisson Disease is a *special predisposition*. This is occasionally strongly marked, some persons being affected by a short exposure to a low pressure from which there would generally be experienced no inconvenience whatever.

The study of these cases has led me to the suspicion that they afford a key to the singular, though very common, predisposition to pains in the limbs on the approach of a storm. These pains are generally considered to be of a rheumatic character, and to depend upon the *dampness* of the atmosphere. But inasmuch as the disease we are considering affords examples of pains precisely the same in character, but immensely intensified in degree, resulting from the diminution of an atmospheric pressure to which the system had adapted it-

* Pneumatologie Medicale. P. 664.

self, and irrespective of any question of humidity, analogy suggests that the so-called rheumatic cases are simply exaggerations of a predisposition, identical in kind with the one under discussion, and are produced by the low barometric condition of the atmosphere which precedes a storm, and not by the influence of moisture. It is true that the change in the pressure is insignificant when compared with that which produces the Caisson Disease, but it is supplemented by the immensely greater duration of the higher pressure to which the subject has been previously exposed. Persons suffering in the manner referred to, regard themselves as walking hygrometers, and are accustomed to say, "I feel the *dampness* in my bones." I would suggest that they are rather barometers, perhaps quite as sensitive as the instrument of Torricelli.

Perhaps the most frequent exciting cause of the Caisson Disease is *too rapid locking out*. Indeed, it is altogether probable that if *sufficient time* were allowed for passing through the lock, the disease would never occur. But what is sufficient time for one is too short a time for another, and as no work could be accomplished if the time in the lock were indefinitely prolonged, all that can be done is to fix upon a duration for the process of locking out which shall be proportioned to the pressure, and as great as is consistent with the circumstances, and then to see that the rule is rigidly observed. The natural impatience of the men to reach their homes, makes the delay in the lock irksome, and great firmness is required on the part of the lock-tender to prevent the escape-cocks being opened more widely than is consistent with safety. In locking out, at least five minutes should always be allowed for each additional atmosphere of pressure.

Neurness to the Work.—Unquestionably the liability to the Caisson Disease is greatest in those exposed for the first time to the influence of the compressed air. New hands are very apt indeed to suffer more or less during the first week, and a number of the severest cases that came to my notice, occurred in men who had worked but a single watch, though first attacks were much more likely to occur after the second watch of the first day. Those least affected were such as began work when the pressure was comparatively slight, and continued without intermission as the pressure increased. It seemed that the system after a time became adapted to the changed conditions, and was protected, in a measure, from their effects. Nevertheless, some serious cases occurred among the old hands, especially when for any reason their stay in the caisson was prolonged beyond the usual time, thus showing that their immunity was merely relative. A sudden increase of pressure, also, even though very slight, was certain to develop new cases—men thoroughly inured to the work often being affected under such circumstances.

Fullness of Habit.—After the work in the New York caisson had been some months in progress it was observed that there was a preponderance of stout, heavily-built men among those taken sick. This led me to examine my records carefully in reference to this point. I found that up to May 22, they embraced 86 cases of well-marked Caisson Disease. These I divided into three classes, according to the build of the individual. Those who were tall in proportion to their weight, and rather lean in flesh, were classed as *spare*; those who were thick-set and muscular, without being fat, were set down as *medium*; and those with prominent abdomen, full cheeks, and general tendency to obesity, were styled *heavy*. The 86 cases of illness were found to be distributed among these three classes as follows: Spare, 28; medium, 22; heavy, 36.

Considering that among laborers below the age of 45 (and none of the cases were above that age), the class described as *heavy* are very much in the minority, these figures were sufficiently striking.

In order to arrive at the converse of this I desired the time-clerk to prepare a list of those who had lost least time from illness, i.e., those least affected by the work. The figures in this case were even more striking. The list comprised the names of 42 men, who were classified as follows: Spare, 25; medium, 14; heavy, 3.

I next separated the severer cases of illness, which were marked by paralysis: of these there were 13: Spare, 2; medium, 3; heavy, 8. Those who had died up that time, three in number, were *all heavy men*.

These results may be tabulated as follows:

	SPARE.	MEDIUM.	HEAVY.	TOTAL.
Lost little or no time from sickness...	25	14	3	42
Taken sick.....	28	22	36	86
Paralyzed.....	2	3	8	13
Died.....	3	3

These figures show unmistakably that a tendency to fullness of habit renders work in a compressed atmosphere much more hazardous. Persons of this build have more fluids in the body, the distribution of which is changed by the pressure, in the manner before stated, and it is therefore not surprising that the effect upon them should be greater than upon lean and sinewy persons, whose bodies contain a minimum of fluid.

Severe Exertion Immediately after Leaving the Caisson.—As at the moment of going out of the compressed air the system undergoes a

violent reaction, it is manifestly unfitted to bear in addition a severe tax upon the muscular strength. Hence, the ascent of a long flight of stairs, immediately after leaving the air-lock, is as wrong in theory as it has proved bad in practice. Dr. Jaminet has described most graphically the ill effects arising from this cause at St. Louis, and the relief experienced when the men were saved the necessity of climbing the steps by the substitution of a steam elevator.* Contrast this with the experience of M. Triger, whose apparatus at Châlonnes was so arranged that the ascent of the ladder took place in the compressed air, the lock being placed at the top instead of the bottom of the shaft. He found that the men ascended a distance of 70 feet without becoming in the least out of breath; making the ascent, in fact, much more easily than if it had been in the open air.

I hoped at one time that an opportunity would be afforded at the New York caisson for obtaining some data bearing upon this point. During the early part of May an elevator was arranged, but unfortunately just at that period great changes took place in the force, and at the same time various interruptions in the work occurred, so that the matter was hopelessly complicated, and no data for comparison could be obtained.

The Abuse of Alcohol.—Several writers have remarked that habitual drinkers are more likely to be affected by compressed air than those who used spirits moderately or not at all. It is stated by the director of the work at Douchy† that the attacks from which the men suffered were "almost always coincident with some excess committed in the interval of the shifts." It is easy to perceive that as the disease is characterized by cerebral congestion, the abuse of alcohol, which has a tendency to produce the same result, would act as a predisposing cause. Although no cases directly attributable to this cause came under my observation, I have no doubt that there is danger from it; and I therefore rejected several men who applied for work in the caisson, for no other reason than that their appearance indicated an habitual excessive use of alcohol.

Entering the Caisson Fasting.—Dr. Jaminet insists very strongly upon the influence of this cause, and cites instances to prove his position. Several cases corroborative of his views occurred under my observation. One of the rules for the men working in the New York caisson, prohibited entering the compressed air without having taken food, and in addition to this each new hand was especially cautioned as to the danger of disregarding this precaution, and the foremen were directed to use every effort to secure its observance. Yet notwithstanding all this a number of very severe attacks were

* See Dr. J.'s Report, p. 120.

† Annales d'Hyg. Pub. et de Med. Legale, 1854.

found to be coincident with, if not dependent upon, violations of this rule. In these cases epigastric pain and retching were prominent symptoms. (See Case XXI., p. 47.)

Treatment.—The treatment of this disease will depend upon the severity of the case, and the presence or absence of gastric symptoms or of paralysis. If we have to deal with the neuralgic pains only, the chief reliance must be upon anodynes, administered with a liberal hand. Fortunately the pain, though very severe while it lasts, is in most cases of short duration, the attack passing off usually in a few hours.

It is, therefore, quite practicable to keep the patient under the influence of morphine during the whole time, and thus enable him to escape entirely all extreme suffering. But large doses will be required, the intense pain inducing a remarkable tolerance of the drug. It was my habit to give half a grain of morphine at the outset, and a quarter of a grain every half hour afterward until relief was obtained. When employed hypodermically, which is the method affording most prompt relief, somewhat smaller doses may be used.

In some instances I have obtained the very best results from hypodermic injections of atropine at the seat of pain; but in other cases it failed to procure relief, and, upon the whole, I consider it inferior to morphine.

Dr. Jaminet, regarding the affection as wholly the result of exhaustion, relies entirely upon stimulants and concentrated nourishment, ignoring the aid of anodynes altogether. I can see no reason for this, even admitting to the fullest extent his theory of the disease, for nothing can be more exhausting than the intolerable pain which characterizes this affection, and nothing could act more promptly as a restorative than an efficient anodyne.

Starting from the theory already given as to the mode in which the disease is produced (a theory which was constructed wholly upon the observations of others), I was led to the idea that benefit would be derived from the use of an agent that would induce contraction of the capillaries, and thus correct the want of tone which I considered to lie at the foundation of the difficulty. For this purpose I proposed the use of ergot before I had ever seen a case of the disease. I reasoned that it would be useful, first, by contracting the vessels of the brain and spinal cord, and relieving their congested state; and secondly, by restoring tone to the superficial vessels, and thus imparting vigor to the circulation.

An extended trial warrants me in saying that the results have justified the theory. In my hands, though not always successful, ergot has certainly been very useful in a considerable number of cases.

I have seen very severe pain completely relieved within half an hour after the administration of a drachm of the fluid extract. In other instances, unsteadiness of the limbs, which seemed about to usher in paralysis, has yielded promptly to one or two doses.

But perhaps the best evidence of its usefulness is to be found in the preference for it of the night-porter, who had charge of the hospital at night, and who was instructed in the use of the few medicines employed, and treated such cases as occurred among the men composing the night gangs. Having both morphine and ergot at hand, he gradually, and of his own accord, almost abandoned the former, declaring that the ergot was more prompt and certain in relieving the pains. This from an intelligent, unprejudiced, non-professional source, is strong testimony in favor of the efficiency of the drug.

I was in the habit of giving a teaspoonful of Squibbs' fluid extract, and repeating the dose in half or three-quarters of an hour, unless the pain was relieved. In one case ergotine was injected hypodermically; but so much irritation was caused at the point of insertion that the experiment was not repeated.

Frictions, with or without stimulating liniments, are very generally resorted to, and seem sometimes to give momentary relief, but it appears to me to be rather by occupying the attention of the patient than by any action occasioned in the part.

In one of my cases of pain in the knee, compression of the femoral artery with the fingers was tried. The pain was considerably relieved for a few minutes, but soon acquired its former severity. In another case a tourniquet was applied so as to interrupt the venous as well as the arterial circulation, but with no better result.

In some instances where the pain was confined to a particular locality, I had the part immersed in hot water, with the effect of causing temporary relief. But the use of the general hot bath was not advised, as I considered it unsafe to increase the already existing relaxation of the vessels. In several of Dr. Jaminet's cases paralysis came on while in the hot bath, and he therefore interdicted its use.

Toward the last of my experience I applied cold to the spine in two cases, with apparent benefit in each. In one of these cases, in which there was paralysis of the bladder, the improvement after a cold douche to the spine was marked.

In one case of paraplegia, dry cups applied to the spine in the lumbar region were unmistakably beneficial.

Electricity was tried by Dr. Jaminet at St. Louis, but was found to be useless.

Epigastric pain is almost always relieved at once by the use of an alcoholic stimulant with ginger, as employed by Dr. Jaminet.

Vomiting is best treated with sinapisms to the epigastrum, and swallowing small bits of ice. A full dose of calomel was effectual in one of my cases which resisted all other treatment.

When paralysis occurs, it is to be treated on general principles. Cups or leeches, with douches and frictions to the spine, may be useful; and if the case be protracted, the use of strychnine may be called for. The bladder will almost certainly be involved, requiring the constant employment of the catheter.

The cerebral symptoms which occasionally occur, are, with the exception of coma, so transient in their nature as to call for no special treatment. Coma, when it takes place, is to be managed according to the circumstances of the case, as when proceeding from other causes. If accompanied by a full, strong pulse, venesection may be expedient.

There remains to be considered a plan of treatment originally suggested by Pol, and carried out to some extent by Foley, viz., returning the patient at once into the compressed air.

It frequently happened under my observation, that pains not sufficiently severe to deter the men from returning to work, were promptly dissipated on entering the caisson, to return again on coming into the open air. Indeed, I do not remember a single exception to the rule, that any pain which may have been felt before, disappeared almost immediately on going below.

Foley says, as the result of his experience: "A true specific is returning to the caisson, through which means all such accidents (pains, vertigo, etc.,) speedily disappear. It is to be resorted to unhesitatingly in all threatening cases, and the pressure should be admitted rapidly."

But the means of access to the caisson are usually such that it would be difficult to remove a patient into it, even if he could be comfortably cared for while there, or if his presence would not interfere with the work. It would, therefore, be desirable to have facilities for employing compressed air at some point above ground which would be easily accessible.

My plan would be as follows: Let them be constructed of iron of sufficient thickness, a tube 9 feet long and $3\frac{1}{2}$ feet in diameter, having one end permanently closed, and the other provided with a door opening inward, and closing air-tight. This tube to be placed horizontally, and provided with ways upon which a bed could be slid into it. Very strong plates of glass set in the door and in the opposite end would admit the light of candles or gas jets placed immediately outside. This apparatus should be connected by means of a suitable tube with the pipe which conveys the air from the condensers to the caisson. An escape-cock properly regulated would allow the constant

escape of sufficient air to preserve the necessary purity of the atmosphere within.

The bed containing the patient having been slid into the chamber, the door is to be closed, and the pressure admitted gradually until it nearly or quite equals that in the caisson. This should be continued until the patient indicates by a signal previously concerted, that the pain is relieved. The pressure should then be reduced by degrees, carefully adjusted to the effect produced, until at last the normal standard is reached. By occupying several hours, if necessary, in the reduction of the pressure, it is probable that a return of the pain could be avoided.

The apparatus once provided, there would be no difficulty in carrying out the plan in any case of such severity as to resist other treatment. I should expect the very best results from it in cases of extreme pain, or in the very outset of paralysis not dependent upon extravasation of blood.

Of course the secondary conditions which arise in protracted cases would not be capable of direct relief by simply reproducing the physical conditions existing in the caisson. The most that might be hoped for in such cases would be that the pressure might result in giving a new impulse to the circulation in the congested part, and thus favor resolution.

Reasoning from his view of the pathology of the disease, M. Bert has proposed the inhalation of oxygen, in order to displace the free nitrogen from the blood by diffusion. Experiments upon animals demonstrated that the sounds produced in the heart by the presence of free nitrogen, speedily disappeared when the animal was made to inhale oxygen, the nitrogen diffusing into this gas much more readily than into common air. But though immediate death was averted by this expedient, paralysis nevertheless occurred, and post mortem examination showed the presence of bubbles of nitrogen in the vessels of the cord.

A tendency to pulmonary congestion seems to be induced by high atmospheric pressure in certain rare instances. Such cases are mentioned by Frangois and Jaminet, and two instances came under my own observation, one of which was almost instantly fatal. (Case XXX.)

The mechanism by which these congestions are produced is not apparent. If in every instance they occurred immediately upon passing from the caisson into the open air, it might be inferred that the expansion of the air contained within the lung produced, in some way, an interference with the pulmonary circulation. But inasmuch as a rapidly fatal congestion may come on an hour or more after leaving the caisson, this explanation is not sufficient. The

subject is involved in obscurity, which can be removed only by the study of a larger number of cases than have occurred as yet.

CHAPTER SIXTH.

ILLUSTRATIVE CASES.

The following cases have been selected from my notes as illustrating the various affections resulting from compressed air which have been described in the foregoing text. Also, a few cases, as will be seen, have been borrowed from other sources.

CASE I.—John Campbell, lock-tender, on the 11th of February, was "caught in the lock," *i. e.*, found himself unable to equalize the pressure in the left ear. The pain, however, not being severe, he completed his day's work. The following night was taken with very severe pain in the ear, which continued without intermission until the 20th, when a profuse discharge of pus from the external ear set in, affording relief from the pain. Under the use of carbolic acid injections the discharge soon ceased, leaving the hearing unimpaired.

CASE II.—John Hicks. Taken on the 17th of May, while in the lock going down, with severe pain in the right ear, followed by a slight discharge from the external meatus. No sensation as of anything giving way in the ear. He completed his watch and then reported to me. On examination, the drum of the ear was found to be ruptured at its upper edge. The opening was nearly circular, and rather less than a line in diameter. The patient preferred to give up his place at once, and did not report again. Though he stated that he had had no previous trouble with the ear, the fact of the discharge when the membrane was ruptured, leads to the suspicion that there was catarrh of the middle ear, which probably accounted also for the stoppage of the Eustachian tube.

CASE III.—Frangois.* Patient at Argenteuil seized with otalgia on coming out of the caisson, where the pressure was 13 lbs. to the inch. Pain persisted for 15 days without intermission, notwithstanding the most active treatment, including purgatives and the application of leeches and antimony behind the ear. Condition of the tube or of the drum not stated.

CASE IV.—Patrick O'Farrell. Reports March 11th, that he was taken four days ago, on going down into the caisson, with pain in the region of the frontal sinus. On coming up, the pain was increased, and there was bleeding from the nose. The pain has continued ever since. Ordered anodynies and hot fomentations.

* *Annales d'Hygiène Publique, et de Med. Leg.* T. XIV. 1860.

14th. Reports for duty.

CASE V.—Hugh Rourke. March 12th, while going home in the evening, was taken with severe pain in the right knee. Pain continued all night. On the following morning he returned to his work, when, on entering the caisson, he found that the pain ceased at once. On coming up again it returned with increased severity. Controlled by morphine.

CASE VI.—John Roland. Taken on March 8th, while in a car going home. Dizziness and loss of strength; feet cold, head hot; unable to stand, but still not paralyzed—simply weak. *No pain.* Profuse cold perspiration. Recovered perfectly in a few hours without treatment.

CASE VII.—Alfred Symes. Suffered somewhat with pain in the right knee, on coming up from the caisson on the 10th of May. On the 11th he worked as usual, experiencing no pain. On the 12th (Sunday), not having been in the caisson since the day previous, he was taken with severe pain in the same knee. When he reported to me, on the 14th, he was suffering with a swelling of the knee, accompanied by heat and extreme tenderness, especially just above the patella. He was ordered to apply fomentations, with a hot solution of bicarbonate of potash. Under this treatment the pain and swelling soon subsided. On the 15th, there was a greenish yellow tinge of ecchymosis over the front of the knee, for a space as large as the palm of the hand.

CASE VIII.—Samuel Mitchell. Worked for one watch only on the 14th of May, being his first experience in compressed air. After the first watch, on the 15th, he was taken with pain in both the upper and lower extremities, and also in the chest and bowels. This was followed by giddiness and vomiting. There was paralysis of the left leg and weakness of the right arm. Profuse sweating. Pulse 80. Ergot and chloral given. Paralysis passed off in two hours, leaving slight pain in the arms and wrists. The bowels had not been opened for several days.

CASE IX.—John Kennedy. This patient had engorgement of the left mammary gland, recurring each day after coming out of the caisson, and especially after the second watch. There was marked swelling and tenderness, which disappeared during the afternoon and evening, to recur again on the following day. This continued for more than a week.

CASE X.—Joseph Hatch. Taken sick on the 17th of May, after his first watch. Epigastric pain and pain in the legs and arms, followed by paraplegia. Treated with ergot only. At the end of four hours he had recovered the use of his limbs, and the pain had ceased, but there remained a giddiness which prevented his standing. By

the following day he was able to walk about, but the giddiness had not entirely disappeared when I last saw him. May 21st.

CASE XI.—E. Riley. Taken sick Feb. 16th, one hour after leaving the caisson. Pressure 26 lbs. Epigastric pain and pain in the legs. No loss of sensibility. Profuse cold perspiration. Pulse, when I saw him, two hours after the commencement of the attack, was 96. The pain, which at first was very severe, had by this time become much less. Gave him an ounce of brandy and a teaspoonful of fluid extract of ergot. In 10 minutes the pulse had fallen to 82. Was able to resume work next day.

CASE XII. Joseph Brown, foreman, American, aged about 28. Taken on the 28th of February, about an hour after coming up from a three hours' watch. Excessive pain in left shoulder and arm, coming on suddenly, "like the thrust of a knife." Pain continued until he went down again for the afternoon watch, when it ceased immediately. On the following morning there was a spot on the shoulder and one on the arm, at the points where the pain had been most severe, where the skin was speckled with minute bright red points of extravasated blood. Had had no pain since the day before, but the parts were tender to the touch, with at the same time a feeling of numbness.

CASE XIII.—Henry Stroud, a diver by occupation, began work on the morning of April 2d. Half an hour after coming up from the first watch, was taken with numbness and loss of power in the right side, also dizziness and vomiting. This was followed by severe pain over the whole body. Excessive perspiration. Was treated with stimulants and ergot, and in five hours was well enough to return home.

CASE XIV.—John Barnabo, Italy, 42, reports that on the 13th of March, while in a car returning home, he was taken with severe pain in both arms. This was followed by dimness of sight and partial unconsciousness. Extremities very cold. Remained in this condition for two hours. Was obliged to keep his bed for three days. For a week afterward was unable to work, feeling very much oppressed about the chest. Had no medical attendance. Had a similar but less severe attack about a month previously.

CASE XV.—J. Avers. Taken on the 7th of April with very severe pain in both knees, coming on within a few minutes after leaving the caisson. A drachm of the extract of ergot was given every hour for three hours, then two more doses at intervals of two hours, after which he was completely relieved.

CASE XVI.—Frank Murphy. Taken sick April 8th, after the second watch of his first day in the caisson. Extremely severe pains in both knees and in the right shoulder; $\frac{1}{2}$ of a grain of atropine was

injected beneath the skin of the shoulder, but afforded no relief. Half a grain of morphia by the mouth did not check the pain. Legs placed in hot water, which gave immediate relief. Ergot was also given in drachm doses hourly. Returned home much better, but the pain subsequently returned, and was very severe at times for several days.

CASE XVII.—Charles Peterson. Taken on the 11th of April with severe pain in both legs and in the right arm. Was relieved by ergot, but had severe pain each day afterward on coming up. On the 15th he was ordered a teaspoonful of the fluid extract of ergot, four times a day, after which there was no further complaint.

CASE XVIII.—Card, foreman. Taken on the 17th of April, after the first watch, with quivering in the thighs, followed by loss of power in the lower extremities, and anæsthesia. There was also partial paralysis of the bladder. These symptoms continued until the 19th, when they disappeared, leaving great soreness of the muscles of the calves. After the paralysis had passed off in a measure, he went down again into the caisson and remained for a short time with decided benefit. The improvement continued after returning to the open air. He had no other medication than two doses of ergot.

CASE XIX.—James Heffener. Attacked May 2d, soon after leaving the caisson, with pain in the limbs and in the epigastrium, followed by vomiting of large pieces of undigested meat. Eyes swollen and very much injected: extreme giddiness: pulse 80, and small. Vomiting continued at intervals for 24 hours. Bowels had not been moved for 48 hours.

Was treated with morphia and ergot, but the vomiting continuing, a scruple of calomel was given on the 3d, which had the effect of quieting the stomach, and at the same time of relieving the bowels, after which the patient quickly recovered.

CASE XX.—Thos. Kirby. Taken April 30, with severe pain in the right forearm. The patient was seen by Dr. G. M. Beard, at whose suggestion I injected into the middle of the palmar aspect of the forearm two minimis of a solution of ergotine, each minim containing a grain of the drug. The following day, considerable swelling had taken place at the point of puncture. The original pain still continued, though less severe. On the 4th day of May, the patient presented himself with a similar, though more extensive, swelling on the other side of the arm, the previous swelling having disappeared. This secondary swelling followed very closely upon the first. It subsided promptly under the use of cold applications: but on the 10th, another similar swelling appeared on the part of the arm above the elbow. It was excessively hot and painful. By the continuous use

of ice, it was soon dissipated without suppuration. The patient did not enter the caisson from the time of the first attack until his final recovery.

CASE XXI.—Brune Wieland, Germany, aged 23. Attacked on the 8th of May, after working two hours in the caisson, which he entered for the first time, and without having taken food. The attack began with pain in the epigastrium, and vomiting soon followed by paraplegia, and great depression. Respiration 40, pulse 100, and very feeble. Stimulants brought about a prompt reaction. The power of motion was soon regained, but there was not sufficient strength in the legs to stand. Paralysis of the bladder. On the following day he was perfectly comfortable, though still too weak to stand. Bladder still paralyzed. Sent to the hospital, after which there is no record of his case.

CASE XXII.—Patrick Rogers, Ireland, aged 40, reported at my office at the pier that the day previous he was taken while on the ferry-boat going home, with pain in the right side, soon followed by loss of feeling and power to move or stand. This was about three-quarters of an hour after leaving the caisson, where the pressure was 26 lbs. to the inch. On the arrival of the boat he was placed in a barge, and taken home. According to his account, he was for four hours completely paralyzed in the legs, and partly so in the arms. A physician was called, who gave a medicine which caused vomiting, after which there was profuse cold perspiration. Symptoms gradually passed off, and by 3 P. M. of the following day he was well, with the exception of weakness and a numb feeling of the skin. A drachm of the fluid extract of ergot was ordered to be given every hour until four doses had been taken. On the 17th, he reported himself as much better. Soon after taking the first dose of ergot, he found his strength improved. He now felt well, except a "trembling" in the chest. Advised not to resume work in the caisson.

CASE XXIII.—Charles Ward. Began work May 17th, and continued through both watches, though advised to omit the afternoon watch for the first day or two. After coming up the second time, he felt some pain in the legs. Did not work again until the 20th, when, after the first watch, he was taken with numbness in the left leg, and partial loss of motion. When I saw him on the 21st, the sensibility in the affected part was very much blunted, but the power of motion was fully restored. Temperature to the hand sensibly lower than in the other leg. No pain. Complaint of a "want of hold upon the ground" in attempting to walk.

Cold water was poured upon the lower part of the spine for several minutes, after which there was a decided improvement in the leg. He was able to walk home; but did not report again, and I lost sight of the case.

CASE XXIV.—Fred. Wilkinson. Taken May 21st, after the second watch, with pain in the right knee. Considerable swelling above and internal to the patella. Slight elevation of temperature. Relieved by the cold douche.

The minutes of the following case were kindly furnished me by Dr. Walter Reed, of the Brooklyn City Hospital, and are so interesting that I transcribe them in full:

CASE XXV.—“Michael Madigan, age 36, Ireland, laborer, admitted March 26th, 1872. A large, robust man: states that he has been working on the East River Bridge for three months past, and that for several weeks past has been under a heavy atmospheric pressure (about 30 lbs.)

“March 25th, about noon, after coming up from the caisson, was taken with cramps in his stomach, which required a dose of medicine for their relief. He then went to his dinner, after which he returned to work, but felt so weak in the legs and in the small of the back that he was compelled to leave off. Was carried home and put to bed. Did not have much pain in the legs or back, but a feeling of extreme weakness. Slept but little during the night, and in the morning found that his legs were powerless, nor could he pass his water, which had to be drawn with a catheter. On admission there was found to be paralysis of the legs, with slight diminution of sensibility. No pain in limbs. Slight tenderness on pressure over the lumbar vertebrae. Paralysis of bladder. Urine drawn off: quantity, 8 oz. Acid reaction: no albumen. Dry cups applied to the lower part of the spine. Ordered liq. ammon., acetatis, to be repeated in an hour. At bed time potas. bromid. grs. 40.

“March 27th. Find patient improved. Slept well during the night. Took some breakfast. Can move his right leg to a considerable extent: left leg powerless. Has slight pain in the back. Urine drawn off, 8 ozs.; acid. P. M., to re-apply dry cups to spine.

“March 28th. Can move both legs very well. Is able to stand, but his knees soon bend under him. Urine drawn off. Cups re-applied.

“March 29th. Can stand up and walk a few steps, though this requires some exertion. Cups again to the spine. Urine drawn off.

“March 31st. Still improves: walked to the water-closet and had a movement of the bowels. This is the second movement since admission. The first was an involuntary evacuation in the bed.

“April 2d. The patient has regained the power over his bladder, and passes his urine twice a day. Feels much stronger.

“April 5th. Patient has been walking about the yard. Says he feels well, except a slight weakness in his back. Discharged cured.”

For some time after his discharge from the hospital, this patient remained very feeble, and the catheter was occasionally required to re-

lieve the bladder. He was confident that he received great benefit from the dry cups while in the hospital, feeling better each time as soon as they were applied. In this statement Dr. Reed concurred.

CASE XXVI.—Reardon, England, 38, corpulent, began work on the morning of May 17th; was advised to work only one watch the first day, but, nevertheless, feeling perfectly well after the first watch, went down again in the afternoon. The pressure at this time was about 35 lbs., the duration of the morning shift $2\frac{1}{2}$ hours, that of the afternoon shift 2 hours. Immediately after coming up from the second watch Reardon was taken with very severe pain in the stomach, followed by vomiting. In a few minutes the pain seized upon the legs, which soon lost the power of motion, though they continued to be the seat of extreme pain, and were not entirely insensible to pinching or pricking. The vomiting continued all night, and toward morning he was removed to the Centre street Hospital, where he gradually sank, and on the 18th died.

The autopsy showed a slight engorgement of the lungs. All the other thoracic and abdominal viscera, as well as the brain, were healthy. The spinal cord was found to be intensely congested, and opposite the two lower dorsal vertebrae, there was an extensive effusion of blood pressing upon the cord.

CASE XXVII.—Patrick McKay, Ireland, 50. Had been four months at work in the caisson, and had not complained of ill-health. On the 30th of April he remained in the caisson half an hour beyond the usual time, at the second watch, the pressure being about 34 lbs. Some other persons who were with him in the lock, when about leaving, found that he was sitting with his back against the wall of the lock, quite insensible. He was at once carried up to the surface, and removed to the Park Hospital, where I saw him shortly afterwards. He was there in an unconscious condition; face pale and dusky; lips blue; pulse irregular and feeble. Under the administration of stimulants, he recovered some degree of consciousness, and begged incessantly for water. The urine was drawn with a catheter, and found to be intensely albuminous. Paroxysms of convulsions soon set in, in one of which he died, nine hours after the attack.

The autopsy, at which I was not present, showed that all the organs were healthy, except the kidneys, which were the seat of Bright's disease, and were very much altered in structure.

In this case the effect of the compressed air was merely to hasten an event which, at best, could not have been very long delayed.

CASE XXVIII.—Frangois. Mirant. Had suffered previously from severe pains in the chest and limbs, which compelled him to give up work. Sometime afterward, when the pressure was 4 atmospheres, he resumed work for a single day—the labor being excess-

sively severe. He suffered no inconvenience apparently, however, and after leaving the caisson, washed his face and hands as usual. A moment after he fell senseless, and in 15 minutes was dead.

The autopsy was made by a medical commission appointed by the authorities of Valenciennes. The meninges were found to be injected, and the sinuses distended with dark blood. The brain itself was also congested. The spinal canal was not opened. The lungs were somewhat congested, especially at the base, where they were less crepitant than natural, though still floating in water even when cut into small pieces. There was general congestion of the abdominal viscera. (*Annales d'Hyg. de Pub. et Med. Legale*, 1860.)

CASE XXIX.—The following description of the post-mortem appearances in a case occurring at St. Louis, is from Dr. Jaminet's report, and may be taken as a type of the morbid anatomy of the Caisson Disease.

"Henry Krausman, 27 years; nativity, Germany; admitted into the hospital March 22d; died the 23d. The whole contents of the cranium were found highly congested, with effusion beneath the arachnoid, the vessels of the latter membrane being highly injected. Blood oozed freely from the substance of the brain on section. The spinal cords presented pathological conditions precisely like those of the brain, with the addition of the existence of clots of extravasated blood at different points inside the dura mater. There was also a congested condition of the thoracic contents, less marked probably in the lungs than in the other organs. The abdominal viscera were very highly congested, with extravasation of blood in the kidneys. The mucous membrane of the bladder was healthy, and a small quantity of bloody urine was in the bladder."

CASE XXX.—John Myers, aged about 40 years, a native of Germany, of a stout, heavy build, commenced work in the caisson for the first time on the 22d of April, 1872, the pressure then being about 34 lbs. to the inch.

He worked during the morning shift of $2\frac{1}{2}$ hours without inconvenience, and remained about the yard for nearly an hour after coming up. He then complained of not feeling well, and started for his boarding-place, which was but a few rods distant. As he passed through the lower story of the house, on his way to his own room, which was on the second floor, he complained of pain in the abdomen. While ascending the stairs, and when nearly at the top, he sank down insensible, and was dead before he could be laid upon his bed.

The autopsy, which took place at the morgue, was made by Dr. Janeway. It showed that the brain, heart, kidneys, and larynx were perfectly normal. The only lesion discovered was in the lungs, which

were congested to a very remarkable degree. The entire extent of both lungs presented an appearance closely resembling that of a highly congested spleen. The spinal canal was not opened; but nothing was found elsewhere to account for the sudden engorgement of the lungs.

CHAPTER SEVENTH.

SUGGESTIONS.

As it is now demonstrated that the method by compressed air is applicable to a great range of engineering operations, and offers many peculiar advantages, it is extremely desirable that the principal objection to its employment, viz., the discomfort and danger to the workmen, should be reduced to a minimum. To this end I would offer the following suggestions, drawn from my own experience and that of European and American observers, to whose writings I have had access.

It is exceedingly desirable that the men should be under control to a certain extent during the intervals of work. Excessive use of intoxicating liquors should be prevented; regular hours for sleep and for meals insisted upon, and sufficient nutritious, digestible, and properly cooked food should be provided. The men should sleep in comfortable beds and in properly ventilated apartments.

All this is manifestly unattainable if the men live in homes of their own choosing. If, therefore, any great work by the aid of compressed air is to be undertaken, the preparations for it should include whatever is necessary for housing and feeding the men at a convenient place near to the work. For this purpose temporary barracks may be erected in an enclosure, which the men should not be permitted to leave except under proper restrictions.

The food should be furnished by the employers, be of good quality, embrace a sufficient variety, and be prepared by competent cooks. Sleeping apartments should be provided, allowing at least 800 cubic feet of air-space to each man, and with facilities for efficient ventilation.

A hospital should be arranged with a sufficient number of beds, and fitted with every appliance necessary for treating patients *during their entire illness*. The hospital to be in charge of a competent steward, under the supervision of a physician, who should attend a portion of each day.

Of course this implies that only single men shall be employed, and that they shall agree at the outset to submit to a *quasi* military rule.

Where the number of men is considerable, as would be the case in any large work, the company could carry out the above suggestions economically to themselves, and after deducting the cost from the pay of the workmen, there would remain to the latter more than they would have left after paying their board in the usual way. At the same time the men would be so much more comfortable than if left to provide for themselves, that they would value the position, and the fear of being discharged would be a sufficient restraint upon them. The tendency, too, would be toward securing at the beginning of the work a set of men who would continue to the end. These men commencing when the pressure was slight, would not be affected by its gradual increase, thus avoiding the great danger which attends those who begin work for the first time after the pressure has attained a high figure. I am satisfied that it is by attention to this point more than by anything else, that the suffering and danger resulting from the use of compressed air may be diminished. (See page 36.)

New hands should not be allowed to work in the caisson more than one watch in each day for the first week, after which half the usual second watch might be added for another week, at the close of which the full time could be entered upon.

Since much of the work on the pier above, as well as in the caisson below, is unskilled labor, it could readily be so arranged that the gangs could work on alternate days in the compressed and in the external air. The advantage of an interval in the caisson work is immediately apparent, the cases of sickness being notably diminished by even a single day's intermission.

The rules given at p. 15 are important, and their observance should be strenuously insisted upon.

The men should be selected as far as possible from those who are of a spare and wiry build, and no one should be accepted who has a tendency to corpulence.

The lock-tenders should be selected with special reference to their trustworthiness, and, if it is found that they cannot be depended upon, the air-cocks should be so arranged that the aperture can be graduated from time by the engineer in charge, so as to prevent the possibility of a too rapid change of pressure.

In entering the caisson, at least three minutes should be allowed in the lock for each additional atmosphere of pressure, and at least five minutes in coming out.

As for the number of hours of work daily, the rule given by Mr. Collingwood will serve as a general guide. "Taking it for granted that 12 hours is the extreme time that a man can labor without detriment to health, in an ordinary atmosphere, then with a pressure of

two atmospheres, or 15 lbs. additional pressure, he can labor about one-half that time; with three atmospheres, about one-third of that time; and with four atmospheres about one-fourth of that time. In other words, the time is inversely as the pressure."*

Whenever, for any cause, a sudden increase of pressure is demanded, the watch should be shortened to a corresponding extent.

The air-locks should be placed at the top rather than at the bottom of the shaft, in order that the stair may be climbed *in the compressed air*, instead of immediately after leaving the lock, when the system is more or less prostrated by the change taking place in the circulation. If, for any reason, it is impracticable to have the air-lock at the top of the shaft, an elevator should be employed to lift the men to the surface.

Care should be taken to maintain the air in the caisson at a sufficient degree of purity, as there may be a wide difference between the amount of air required to supply the necessary mechanical conditions for carrying on the work, and the quantity demanded for the health of the workmen. A rough but useful test for the presence of carbonic acid in the air has already been described at p. 14. This is very easily applied, and should be frequently resorted to when there is the least doubt as to the sufficiency of the air supply. A comparison of the results with those obtained in some fairly ventilated apartment, will give an idea of the amount of impurity in the air of the caisson. The comparison will be aided by allowing the carbonate of lime formed to settle to the bottom of the test tube, where the quantity can be more readily appreciated.

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* Trans. Am. Society of Civil Engineers, p. 133.